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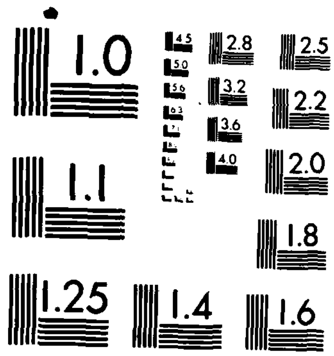

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

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Program Engineering
and Maintenance Service
Washington, D.C. 20591

The Stapleton Microburst Advisory Service Project
An Operational Viewpoint

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Transportation Systems Center
Cambridge MA 02142

September 1985
Final Report

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U.S. Department of Transportation
Federal Aviation Administration

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16. Abstract

A microburst advisory service project was conducted at Stapleton International Airport for a six week period during the summer of 1984. This report describes what took place during the project and what was learned from an operational, air traffic control viewpoint. Specifically, the report describes:

1) The operational, Doppler weather radar-based, microburst advisory service provided to pilots;

2) An unplanned and informal, Doppler radar-based, gust front advisory service initiated partway through the project and used by the FAA for runway management purposes;

3) The operational impact on runway operations of an unexpected, low-altitude, wind shear feature in which individual microbursts form a relatively long-lived line structure; and

4) The low-altitude wind shear environment faced by Stapleton controllers and pilots during the six week project, which took place at the peak of the Denver thunderstorm season.

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PREFACE

This study was performed by the U.S. Department of Transportation, Transportation Systems Center, Cambridge, MA. The study is sponsored by the U.S. Department of Transportation, Federal Aviation Administration, Program Engineering and Maintenance Service, Primary Radar Program Office, APM-310.

The study was conducted in support of a microburst advisory service project conducted at Stapleton International Airport. The purpose of the study is to describe what occurred from an operational air traffic control viewpoint.

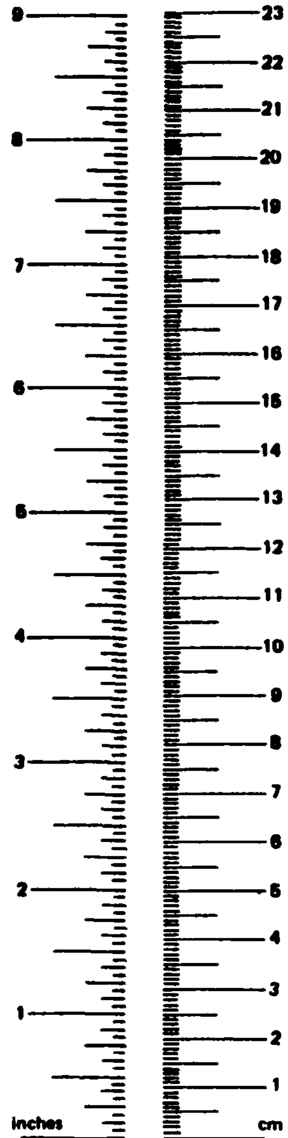
The data collection activity and follow-up analysis involved the cooperation of two organizations and many individuals. The support provided by the: (1) Classify, Locate and Avoid Wind Shear (CLAWS) Project of the National Center for Atmospheric Research (NCAR) and (2) the Air Traffic Service at Stapleton International Airport is gratefully acknowledged.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

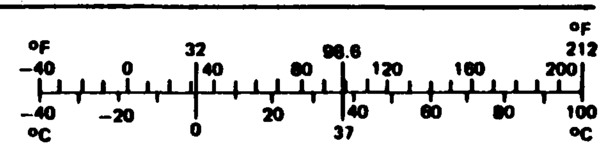
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in. = 2.54 cm (exactly). For other exact conversions and more detail tables see NBS Misc. Publ. 286, Units of Weight and Measures. Price $2.25 SD Catalog No. C13 10 286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	36	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1. INTRODUCTION

An operational microburst advisory service was provided at Stapleton International Airport for a six week period during the summer of 1984. Microburst advisories were issued to pilots on final approach, awaiting takeoff clearance and on initial takeoff climb. A microburst is a small, short-lived, low-altitude, thunderstorm-related, wind shear feature that can exhibit an intense, complex wind shear pattern that can be particularly hazardous to landing and departing aircraft.

The purpose of this report is to describe what took place and what was learned from an operational Air Traffic Control (ATC) viewpoint. A companion report (Reference 1-1) written by Dr. John McCarthy et. al. from the National Center for Atmospheric Research (NCAR) describes what was learned from a meteorological standpoint and from the point of view of setting up and operating a real-time microburst detection service for aviation use. Reference 1-2 is an early NCAR paper describing the project.

Background

The advisory service was initiated in response to a microburst related incident that occurred at Stapleton on May 31, 1984. A Boeing 727 departure encountered a wind shear condition on takeoff roll and liftoff that resulted in the aircraft striking an instrument landing system antenna approximately 1100 ft beyond the departure end of the runway. The aircraft returned safely to the airport and was found to have two gashes in its fuselage. NCAR, which at times operates one or more Doppler weather radar units in the vicinity of Stapleton for meteorological research purposes, verified that the departure had encountered a microburst.

Based on this incident and the results of the 1982 NCAR Joint Airport Weather Studies (JAWS) Project, which showed microbursts to be a common feature in the vicinity of Stapleton during the thunderstorm season, the Federal Aviation Administration (FAA) requested that NCAR use one of its Doppler weather radar units to set up and operate a microburst advisory service to the Stapleton control tower during the 1984 thunderstorm season. NCAR had the service in operation by early July.

The service remained in operation for a six week period during the peak of the Denver thunderstorm season. The service was named CLAWS for Classify, Locate and Avoid Wind Shear.

In addition to satisfying a current operational need, CLAWS represented a simple example of one type of Doppler based weather product/service that the FAA would eventually like to provide to its controllers and the aviation community on a regular basis. The FAA is pursuing this goal with its participation in the Next Generation Weather Radar (NEXRAD) Program with the Department of Commerce and the Department of Defense and with its own Terminal Area Doppler Weather Radar Program. When a national network of Doppler weather radars becomes operational in the early part of the next decade, the FAA plans to introduce a number of Doppler based weather products designed for ATC and aviation community use.

To put it into perspective, CLAWS represented the first introduction of a near real-time, Doppler-based product into a control tower operation - the microburst advisory. During the course of the project, NCAR found itself dealing with two other low-altitude wind shear features of operational significance to aviation and ATC: (1) *the wind shift line (e.g., gust front)* and (2) *an unexpected feature with* an elongated, long-lived outflow caused by a line of microbursts and called a "microburst line" in this report.

Primary Findings

Much was learned from an operational viewpoint. The primary findings are these:

1) The Doppler radar based microburst advisory service was a success in that : (A) it provided timely advisories for 20 microbursts over the six week test period and (B) Stapleton controllers expressed the view that the advisories increased operational safety in their opinion and that the service was worthwhile.

2) An unplanned and informal, Doppler-radar-based, gust front advisory service was a success in that Stapleton watch supervisors expressed the view that the advisories made planning for runway changes due to wind shift lines much more efficient and that these advisories proved to be the greatest benefit of the program from an Air Traffic management standpoint.

3) In response to the enthusiastic embrace of the gust front advisory for runway management purposes, brief follow-up discussions were conducted with three Stapleton watch supervisors in an attempt to quantify the advisory's potential benefit. Based on those discussions, a first-cut estimation of the potential savings for Stapleton was calculated to be $875K per year.

4) For the first time, case studies were obtained documenting the microburst line as a significant aviation hazard that can disrupt runway operations for up to 30 minutes.

A discussion of all the findings along with recommendations are presented in Section 6. The reader may wish to proceed directly to Section 6 and then to the rest of the report, if more detail is desired.

Section 2 presents a description of the project's implementation. The microburst and gust front advisory services are described in Sections 3 and 4, respectively. Finally, Section 5 presents additional operational insights provided by the opportunity to study the effect of low-altitude wind shears on Stapleton runway operations over a six week period.

2. IMPLEMENTATION OF THE ADVISORY SERVICE

This section briefly introduces the basic elements of the project, specifically:

1) The Doppler weather radar unit used as the basis for the advisory service,

2) The radar scanning strategy,

3) Radar siting implications, and

4) The basic NCAR support and procedures used to implement the advisory service.

The section concludes with a summary of the key factors characterizing the implementation.

Doppler Weather Radar Unit

The weather radar facility on which the advisory service was based was NCAR's CP-2 unit, which is located near Denver. The CP-2 contains both a 10 cm (S-band) Doppler weather radar and a 3 cm (X-band) reflectivity-only weather radar. The 10 cm Doppler weather radar:

1) Is a state-of-the-art radar similar to the Next Generation Weather Radar (NEXRAD) unit currently being developed by the Federal Goverment.

2) Was the primary radar used in the detection of microbursts during the advisory service.

3) Did not have a ground clutter suppression filter. (The clutter environment in the vicinity of Stapleton is significant.)

The 3 cm reflectivity-only weather radar:

1) Had a ground clutter suppression filter.

2) Played an important secondary role during the advisory service in that it was used to supplement information from the 10 cm reflectivity channel in the search for microbursts in high density clutter areas (i.e., to support the use of reflectivity as well as Doppler radar information by NCAR in its search for microbursts).

Prior to this project, the CP-2 had been used for several years by NCAR in its research into storm structure including the origin, structure and life cycle of the microburst.

Radar Scanning Strategy

The radar volume scan used for the advisory service consisted of six, 360 degree elevation scans made over a 2.5 minute period. The two lowest scans were fixed and made at .2 and .9 degrees above the horizon. The upper four elevation scan angles varied depending on atmospheric conditions, which controlled the height at which the Doppler radar would find the horizontal inflow of air supplying a microburst's downflow. Typically, the four upper elevation scans were made at 2.5, 3.5, 5.5 and 10.0 degrees.

Radar Siting Implications

In its research, NCAR meteorologists have routinely observed microbursts in the vicinity of Stapleton over the past several years using the CP-2 unit. However, the siting of CP-2 relative to providing full microburst coverage of Stapleton was not optimal from a distance or terrain standpoint.

Ideally, a Doppler weather radar providing microburst coverage for an airport should be located within 10 nautical miles (i.e., 18 km) of the airport. This distance is based on considerations of both the resolution needed to adequately detect small wind shear features, like a microburst, and the signal strength needed to detect microburst outflows in clear air. The CP-2 site was 34 km from Stapleton center field.

Secondly, the lowest radar antenna scan at .2 degrees was blocked by the terrain from seeing the final 850 to 1050 ft. of airspace above the runways in the vicinity of Stapleton. The blocked view of this airspace was the sum of three components:

1) The CP-2 site was located at an elevation approximately 450 ft. above Stapleton's runways.

2) A ridge in the direction of Stapleton blocked the beam below .1 to .2 degrees above the horizon over the 30 degree arc of interest for an additional 200 to 400 ft. loss in altitude coverage over Stapleton.

3) The earth's curvature over the 34 km distance to Stapleton caused an additional 200 ft. loss in altitude coverage.

This blockage below 1000 ft. was of concern for two reasons. First, the radar would not measure the peak horizontal winds in a microburst's outflow which typically occur at altitudes below 1000 ft. above-ground-level (AGL). Second, microbursts with a shallow outflow could be missed.

Implementation of NCAR's Microburst Advisory Service

The radar is only one element of a microburst advisory system. Two other key elements to implementing such an advisory system are the means used to:

1) Scan the radar return for microbursts

2) Transmit the critical microburst information from the radar site to the control tower.

The FAA envisions that both these functions will ultimately be done automatically without requiring an in-line human operator between the radar and the control tower. Such a fully automated implementation was not feasible at the time of the project.

Circumstances only permitted NCAR a few days to plan and implement the advisory service. NCAR used four in-line operating positions, staffed by experienced meteorologists, to implement the microburst detection and the radar site to control tower data transmission functions. The basic responsibilities of these four operating positions were that the:

1) First meteorologist, located at the radar site, would scan the radar display for the presence of microbursts in the vicinity of Stapleton.

2) Second meteorologist, located beside the first operator, would transmit information on any detected microburst to the control tower via a radio voice link.

3) Third meteorologist, located in the Stapleton control tower cab with the controllers, would receive the microburst information via the radio link.

4) Fourth meteorologist, also located in the Stapleton control tower cab, would issue, update and cancel the NCAR microburst advisories passed on to the FAA (i.e., the watch supervisor in the tower cab).

Summary of Key Factors

This initial implementation of a microburst advisory service was characterized by:

1) The marginal siting of the Doppler radar relative to providing full Stapleton coverage for microbursts (operational implication - it was felt at the beginning of the project that the radar would probably miss some Stapleton microbursts and that the advisories might not be as accurate as they would have been if the radar had been properly sited for the task.)

2) The manual monitoring of the radar display for several hours at a time for an infrequent target - a microburst (operational implication - this was a second potential source of missed or late microburst detections since even highly skilled and motivated radar operators, as were used in the project, will normally have trouble maintaining their initial levels of alertness over extended periods of time.)

3) The use of a radio-voice communications link to transmit radar-based microburst data from the radar site to the control tower (operational implication - this low speed data link made it necessary to keep the microburst advisory product simple).

In an attempt to compensate for possibly late or missed radar detections, the two NCAR meteorologists positioned in the control tower monitored: (i) Stapleton's Low-Level Wind Shear Alert System (LLWAS) for indications of a possible microburst outflow on the airport's surface and (ii) the scene around the airport as seen from the tower cab windows for visible cues of a microburst, such as blowing dust caught up in a microburst's outflow. The meteorologists came to issue advisories based on these two non-radar sources.

3. THE MICROBURST ADVISORY SERVICE

NCAR provided a microburst advisory service to the Stapleton Air Traffic Control Tower (ATCT) from 11 am to 8 pm daily for a six week period in July and August of 1984. This section presents:

1) A description of that service, and

2) The six week record of both the advisory service and the operational impact of microbursts on Stapleton's arrival and departure operations.

3.1 THE MICROBURST ADVISORY SERVICE IN OPERATION

Microbursts are low-altitude, wind shear features that are of primary concern to pilots while on final approach to an airport, awaiting takeoff clearance, and on their initial takeoff climb. Pilots in these phases of flight are the responsibility of the local controller who directs the runway operation from the ATCT.

Figure 3-1 shows the layout of Stapleton's primary runways. Stapleton has two sets of parallel runways located at right angles to one another. Typically, one set of parallel runways is used to handle arrivals while the second set is used for departures. Stapleton staffs two local control positions - one for each set of runways.

Figure 3-1 also shows the initial microburst coverage provided by NCAR. NCAR issued advisories for microbursts that fell within five nautical miles of Stapleton center field (i.e., the ASR-8 antenna site). This ten nautical mile diameter circle provided approach coverage out to at least 2.5 nautical mile final for all runways, where approaching aircraft are still 850 ft. AGL.

Typically, microburst advisories were initiated by the meteorologist that scanned the radar display at the CP-2 site. The meteorologist applied an algorithm to the displayed radar data to determine when an observed outflow feature in the vicinity of Stapleton warranted an advisory. This algorithm evolved over the test period.

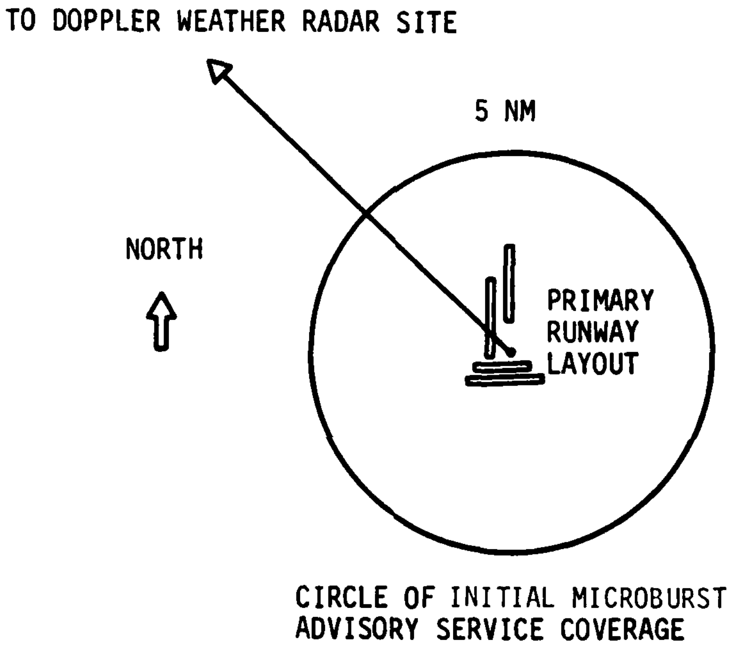


FIGURE 3-1: BASIC LAYOUT

A simplified version of the final form of the algorithm is:

1) If the distance across the outflow as measured between the velocity peaks is less than or equal to 4 km and the measured differential peak to peak velocity is between 10 to 25 m/sec, then initiate an advisory for a microburst with a potential for 50 kt wind shears across the outflow. (It should be noted that the CP-2 did not measure a microburst's actual peak horizontal wind shear intensity across its outflow because the peak: (i) is highly directional within the outflow and cannot be measured by a single radar and (ii) typically occurs below 1000 ft. AGL and could not be viewed directly by the CP-2 radar complex (Section 2).)

2) Or if the differential measured peak to peak velocity is greater than 25 m/sec, then initiate an advisory for a microburst with the actual observed differential wind speed (i.e., for some value over 50 kts).

3) Or if the distance across the outflow's peak to peak velocities is from 4 to 10 km and there is a measured velocity gradient of 10 m/sec or more over a 4 km distance, then initiate an advisory for a microburst with a potential for 50 kt wind shears across the outflow.

When one of these three conditions was met, the location of the microburst's center would be relayed to the control tower, via the radio voice link, along with the appropriate wind shear strength. Microburst locations were given in terms of their direction and distance from Stapleton center field (i.e., the ASR-8 antenna site).

On receipt of this information by the NCAR meteorologist in the ATCT in radio contact with the radar site, a microburst advisory sheet would be filled out. The meteorologist would note the date, Greenwich mean solar time, the distance and direction of the microburst center from Stapleton center field, and the outflow's potential wind shear strength. Figure 3-2 shows an example microburst advisory sheet. The meteorologist would then attempt to draw the approximate location of the outflow's boundary on the map showing Stapleton's runways.

CXG 2317

DATE 8/15 TIME 2312

WEATHER RADAR INDICATES A MICROBURST 5 MILES E (Direction) OF

STAPLETON. WIND SHEAR MAY BE 50 KNOTS.

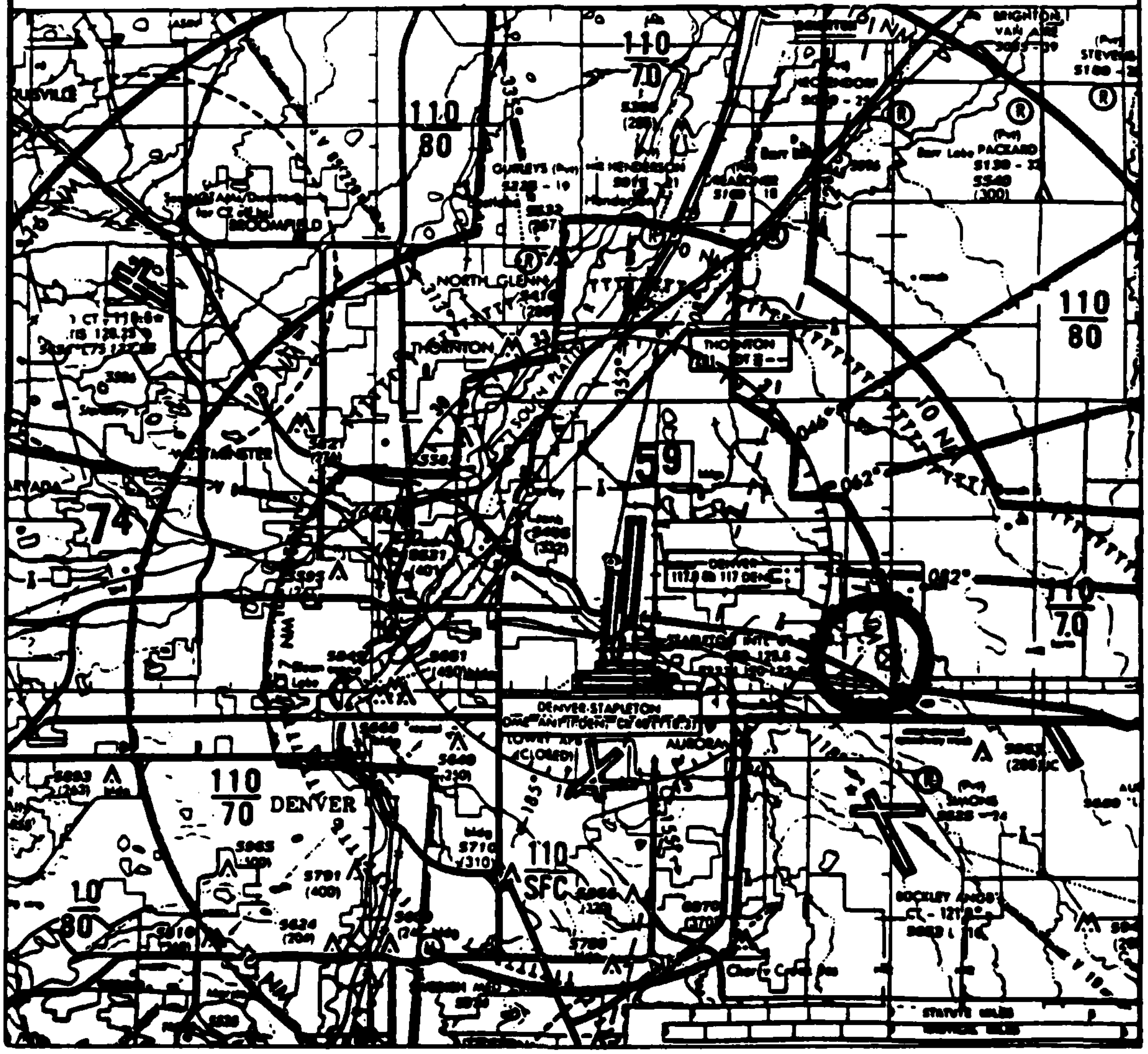


FIGURE 3-2: EXAMPLE OF THE MICROBURST ADVISORY SHEET USED BY CONTROLLERS

It was recognized at the start of the project that this map showing the boundary of the microburst relative to the runways should be based on the radar display presentation. However, the low-speed, voice data link prevented information of this detail from being used.

NCAR would then issue the microburst advisory to the FAA by passing the advisory sheet to the watch supervisor in the control tower. The supervisor would pass on the advisory sheet to one or both local controllers, depending on the distance of the microburst to the arrival and departure runway operations.

The local controller would then issue the advisory to pilots. In the case of the advisory presented in Figure 3-2, the controller would read "Weather radar indicates a microburst 5 miles east of Stapleton. Wind shear may be 50 knots".

The FAA gave an advisory the same weight as a pilot report of a wind shear encounter. After the first reading of the advisory, the local controller was free to reissue the advisory as she or he considered appropriate. For example, a microburst located some distance from the runway operation may only be issued once, but a microburst located near the operation may be reissued to each pilot on initial contact until the advisory is cancelled by NCAR.

The NCAR meteorologist would walk over to the local controller station both to update the advisory, if the center of the microburst moved significantly, and to cancel the advisory. In the Figure 3-2 example, the microburst was stationary and was cancelled (i.e., CX) at 2317 or 5 minutes after the advisory was issued.

An Example - A Microburst that Cut Across Stapleton's Arrival Operation

Before proceeding with an actual case study of aircraft on final approach encountering a microburst, the reader may find it instructive to briefly review the characteristics of a microburst. Figure 3-3 shows the basic vertical and horizontal wind structure of a microburst and the type of airspeed variations that a pilot would experience in flying through a microburst's outflow. Table 3-1 presents some of NCAR's findings and observations characterizing microbursts in the Denver area. These are typical values and are not statistical in nature.

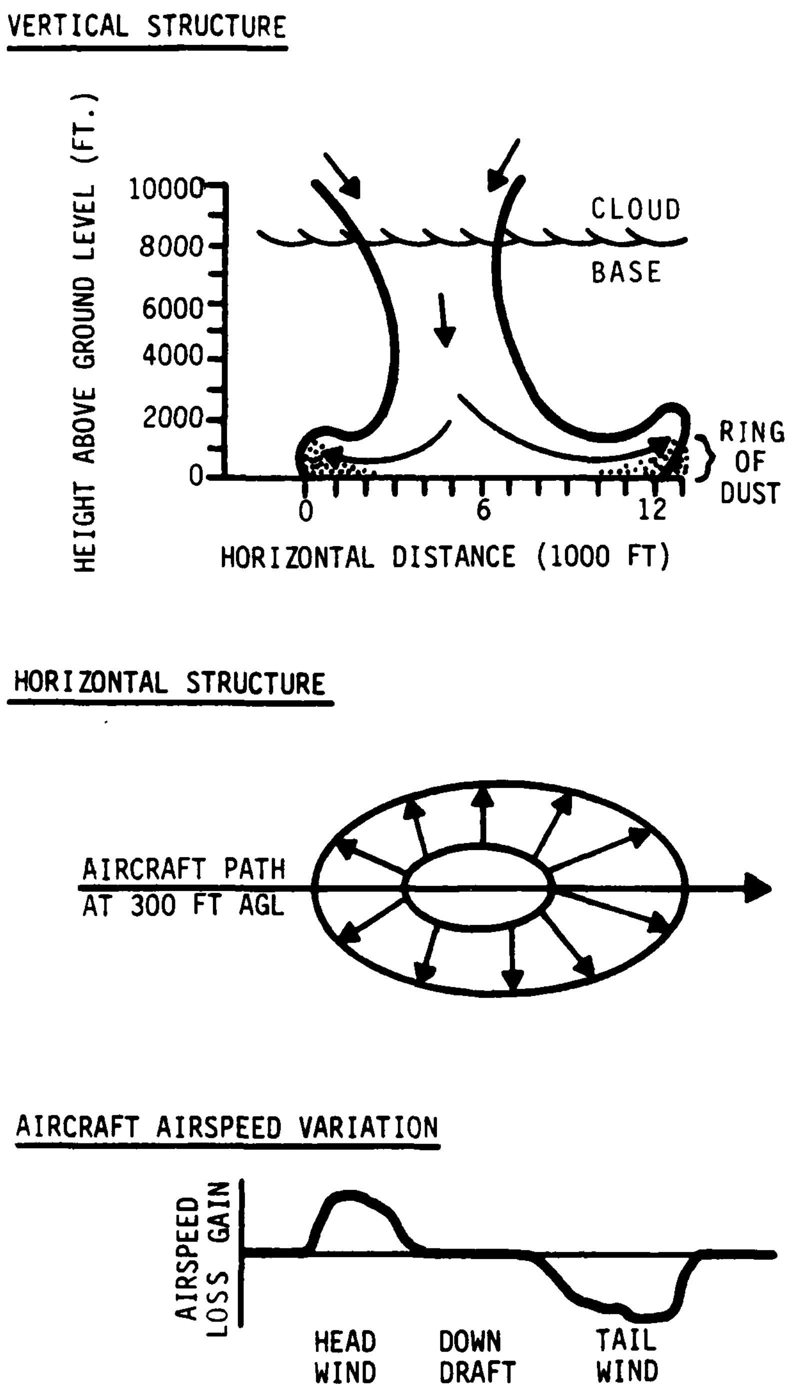


FIGURE 3-3: MICROBURST STRUCTURE AND AIRCRAFT AIRSPEED VARIATION DUE TO A MICROBURST ENCOUNTER

1) TYPICAL OUTFLOW DIAMETER AT ONSET	1 TO 3	KILOMETERS
2) TYPICAL OUTFLOW DEPTH	1000 TO 3000	FEET
3) TYPICAL VELOCITY DIFFERENTIAL ACROSS OUTFLOW	50	KNOTS
4) MAX. OBSERVED VEL. DIFF. ACROSS OUTFLOW (DENVER AREA)	93	KNOTS
5) TYPICAL HEIGHT OF MAX. HORIZONTAL OUTFLOW WIND:		
• MICROBURSTS AT GROUND LEVEL	75 TO 400	FEET (AGL)
• MICROBURSTS HELD ALOFT ①	UNKNOWN	FEET (AGL)
6) TYPICAL OUTFLOW LIFETIME	5 TO 15	MINUTES
7) TYPICAL TIME FOR OUTFLOW TO REACH MAX. STRENGTH	3 TO 8	MINUTES
8) TYPICAL DURATION OF MAXIMUM STRENGTH	2 TO 4	MINUTES
9) AT STAPLETON, ESTIMATED:		
• RATIO OF MICROBURSTS REACHING THE SURFACE VERSUS THOSE HELD ALOFT ①	VAST MAJORITY REACH SURFACE	
• RATIO OF STATIONARY MICROBURSTS ② TO TRAVELING MICROBURSTS ③	ABOUT 80%	

NOTES

① A MICROBURST CAN BE HELD ALOFT BY A LAYER OF RELATIVELY COLD AIR NEAR GROUND LEVEL

② A STATIONARY MICROBURST IS ONE WHOSE CENTER STAYS WITHIN 2KM OF ITS STARTING LOCATION OVER THE MICROBURST'S LIFETIME

③ SOME MICROBURSTS TRAVEL 4NM OR MORE DURING THEIR LIFETIMES

TABLE 3-1: MICROBURST CHARACTERISTICS IN THE DENVER AREA

On August 5, 1984, a microburst hit the arrival runways and then traveled along the final approach path where it was encountered by a large number of aircraft. Figure 3-4 summarizes the facts in the case. NCAR issued an advisory for the microburst at 5:51 pm. The advisory was for a microburst centered one mile north of Stapleton center field with a potential wind shear strength of 70 kts. It is seen that the microburst was on the north-south arrival runways but was probably clear of the east-west departure runways. The local controller handling the arrivals started to issue the advisory to pilots on final approach at 5:52 pm. The controller continued to issue the advisory to each arrival at initial contact until 6:07 pm. Based on CP-2 information, NCAR updated the advisory at 6:00 pm with a new location of 4 miles north of Stapleton center field and a potential wind shear strength of 40 kts versus the original 70 kts.

A steady stream of arrivals were landing on both north-south runways during the time that the advisory was in effect. No pilot reports were received while the microburst was well back on the runways. The first pilot report (PIREP) was received at 5:58 pm, seven minutes after the advisory had been issued by NCAR. By that time the microburst was coming off the runways and the pilot probably encountered a headwind before landing, "a real good shear there." Within a couple of minutes, the microburst was off the runways and pilots were reporting flying through both sides of the outflow, "plus and minus 20 kts on final." A few minutes later, the microburst had moved far enough out on final approach that aircraft were flying over the front side of the outflow but still descending into the tailwind portion of the outflow, "20 kt loss about 1 mile out." The final PIREP was received at 6:08 pm, "a pretty stable approach."

Between the first and last encounter PIREP, 16 aircraft landed and probably encountered the microburst. There were no missed approaches.

The advisory was timely. The NCAR advisory preceeded the first encounter PIREP by seven minutes and the maximum strength encounter PIREP at 6:02 pm by eleven minutes.

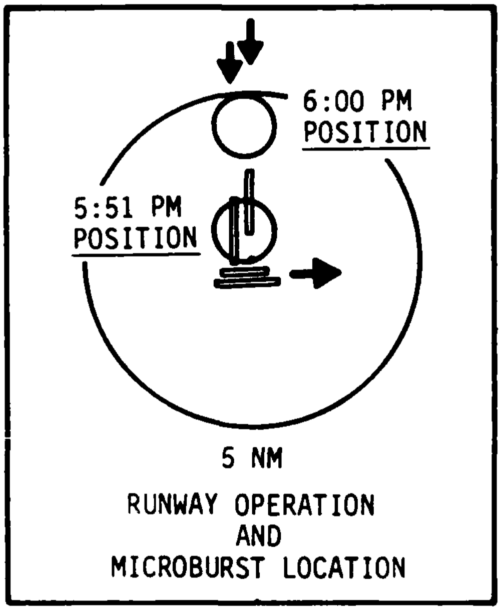
The advisory wind shear estimate was 15 kts low. The maximum strength encounter at 6:02 pm was for an overall wind shear of 55 kts. The estimated top wind shear strength on the 6:00 pm advisory was for 40 kts.

NCAR ADVISORY

DATE:	AUGUST 5, 1984
ISSUED:	5:51 PM (6:00 PM)
LOCATION:	1 MILE N (4 MILES N)
STRENGTH:	70 KTS. (40 KTS.)

FAA ADVISORY VIA CONTROLLER

N-S CONTROLLER:	5:52 TO 6:07 PM
E-W CONTROLLER:	NOT ISSUED



MICROBURST RELATED PIREPS

A STEADY STREAM OF ARRIVALS TO THE N-S RUNWAYS LANDED BETWEEN 5:50 AND 6:10 PM

5:58 (17R ARR.)	"A REAL GOOD SHEAR THERE"
5:59 (17L ARR)	"IT GOT REAL EXCITING"
5:59 (17L ARR.)	" + AND – 20 KTS ON FINAL"
6:02 (17R ARR)	REPORT OF + 25 FOLLOWED BY A – 30 KTS AT 450 FT AGL
6:04 (17L ARR)	"A GOOD SHEAR THERE AT 150 FT"
6:06 (17L ARR)	"20 KT LOSS ABOUT 1 MILE OUT"
6:08 (17L ARR)	"A PRETTY STABLE APPROACH"

NUMBER OF MISSED APPROACHES: NONE

NCAR ADVISORY ASSESSMENT

TIMELINESS:	ADVISORY 7 MIN. EARLY (1ST PIREP)
STRENGTH:	ADVISORY 15 KTS LOW

FIGURE 3-4: DETAILED LOOK AT ONE MICROBURST

This case is unusual because it involved a microburst that was not essentially stationary during its lifetime (see Table 3-1), that travelled along the final approach path, and that was encountered by so many aircraft. However, the case is a representative example of the other cases observed during the project relative to:

1) The reaction of pilots to a microburst on final approach

2) The operation of the microburst advisory service.

3.2 THE MICROBURST ADVISORY SERVICE - THE SIX WEEK RECORD

Thirty microbursts were observed within five nautical miles of Stapleton center field during the six week operational period. Table 3-2 summarizes the pertinent facts for each of these microbursts in terms of:

1) The NCAR advisory issued, including the: (a) time that NCAR issued the advisory (i.e., passed the advisory sheet to the watch supervisor in the control tower), (b) location of the microburst (i.e., the distance and direction of the microburst center from Stapleton center field), (c) the maximum horizontal wind shear that could be experienced by a pilot flying through the outflow, (d) operational status of the CP-2 radar unit when the advisory was issued and (e) the source of the advisory (i.e., the CP-2, a visual sighting from the tower of dust caught up in the outflow, the Low Level Wind Shear Alert System (LLWAS) or a pilot report of a microburst type wind shear encounter)

2) The time for the first FAA announcement of the advisory

3) The operational impact of the microburst, including the : (a) number of arriving and departing pilots reporting an encounter with the microburst, (b) time and strength of the first reported encounter, (c) time and strength of the maximum strength encounter, (d) estimated number of aircraft that flew through the microburst between the first and last encounter PIREPs, (e) number of missed approaches (i.e., go-arounds) and (f) duration that departures delayed their takeoffs

	MICROBURST CASE NUMBER 1	2	3	4	5	6
DATE	7-6-84	7-6-84	7-6-84	7-7-84	7-7-84	7-7-84
NCAR ADVISORY						
• TIME ISSUED (LOCAL DENVER TIME)	2:25 PM	NOT ISSUED ①	5:14 PM	2:31 PM	3:25 PM	4:11 PM
• DIST. (NM) DIRECTION FROM CENTER FIELD	5NW		5NNE	3WNW	3NW	5NW
• POTENTIAL MAXIMUM WIND SHEAR STRENGTH	40 KTS		20 KTS	40 KTS	50 KTS	40 KTS
• CP2 OPERATIONAL STATUS	UP	UP	UP	UP	UP	UP
• SOURCE OF ADVISORY	CP2	NO ALERT	TOWER SIGHT ②	TOWER SIGHT ③	TOWER SIGHT ③	CP2
TIME OF FIRST FAA ANNOUNCEMENT OF ADVISORY	2:27 PM	NOT ISSUED	NOT ISSUED	NOT ISSUED	3:26 PM	4:12 PM
OPERATIONAL IMPACT OF MICROBURST (MB)						
• No OF ARRIVAL ENCOUNTER PIREPS	NONE	4	5	5	NONE	NONE
• No OF DEPARTURE ENCOUNTER PIREPS	NONE	NONE	NONE	NONE	NONE	NONE
• FIRST ENCOUNTER	-	2:36 PM (± 20 KTS)	5:12 PM (-15 + 20 KTS)	2:29 PM (MOD CHOP)	-	-
• MAXIMUM STRENGTH ENCOUNTER	-	SAME	SAME	2:36 PM (+ 30 -20KTS)	-	-
• EST. No OF AIRCRAFT THAT FLEW THROUGH MB	0	5 ARRIVALS	11 ARRIVALS	6 ARRIVALS	0	0
• No OF MISSED APPROACHES	NONE	NONE	NONE	NONE	NONE	NONE
• DURATION THAT DEPS DELAYED TAKEOFFS	0	0	0	0	0	0
IF MICROBURST NOT CONFIRMED BY AN ENCOUNTER PIREP, SHOULD IT HAVE BEEN?	NO	CONFIRMED	CONFIRMED	CONFIRMED	NO	NO
TIMELINESS OF NCAR ADVISORY						
• FIRST ENCOUNTER	-	-	2 MIN LATE	2 MIN LATE	-	-
• MAXIMUM STRENGTH ENCOUNTER	-	-	2 MIN LATE	5 MIN EARLY	-	-

NOTES

① PROBABLE CAUSE - SATURATION OF THE NCAR TEAM DUE TO A WIND SHEAR SITUATION INVOLVING TWO MICROBURSTS, A GUST FRONT, AND A TORNADO WITHIN 5NM OF STAPLETON

② PROBABLE CAUSE FOR THE MISSED CP2 DETECTION - WEAK CLEAR AIR RADAR RETURN FROM STAPLETON DUE TO SHOWERS WASHING TRACERS OUT OF THE AIR

③ PROBABLE CAUSE FOR THE MISSED CP2 DETECTION - NCAR ATTENTION ON INTERMITTANT CP2 OPERATION DURING STARTUP OF SERVICE

TABLE 3-2: SUMMARY OF MICROBURST CASES

	MICROBURST CASE NUMBER 7	8	9	10	11	12
DATE	7-7-84	7-7-84	7-7-84	7-10-84	7-15-84	7-20-84
NCAR ADVISORY						
• TIME ISSUED (LOCAL DENVER TIME)	4:16 PM	4:23 PM	4:32 PM	3:42 PM	2:30 PM	4:20 PM
• DIST. (NM) DIRECTION FROM CENTER FIELD	ON AIRPORT	ON AIRPORT	2 SE	4N	NOT GIVEN	1NNW
• POTENTIAL MAXIMUM WIND SHEAR STRENGTH	50 KTS	55 KTS	45 KTS	30 KTS	NOT GIVEN	50 KTS
• CP2 OPERATIONAL STATUS	UP	UP	UP	UP	UP	UP
• SOURCE OF ADVISORY	CP2	CP2	TOWER SIGHT ①	LLWAS ②	PIREP ③	CP2
TIME OF FIRST FAA ANNOUNCEMENT OF ADVISORY	4:16 PM	4:23 PM	NOT ISSUED	3:42 PM	NOT ISSUED	NOT ISSUED
OPERATIONAL IMPACT OF MICROBURST (MB)						
• No OF ARRIVAL ENCOUNTER PIREPS	1	0	7	0	9	0
• No OF DEPARTURE ENCOUNTER PIREPS	2	3	0	1	0	0
• FIRST ENCOUNTER	4:20 PM (SQUIRRELLY)	4:33 PM (10 KTS)	4:27 PM (15 KTS)	UNKNOWN ④ (CLIMB PROB.)	2:25 PM (HVY WIND SHR)	NONE
• MAXIMUM STRENGTH ENCOUNTER	4:22 PM (+20KTS)	SAME	4:36 PM (±30 KTS)	SAME	2:28 PM (-30 KTS)	NONE
• EST. No OF AIRCRAFT THAT FLEW THROUGH MB	1 ARR 2 DEP	6 DEPS	8 ARRIVALS	1 DEP	12 ARRIVALS	0
• No OF MISSED APPROACHES	NONE	NONE	2	NONE	1	NONE
• DURATION THAT DEPS DELAYED TAKEOFFS	< COMBINED	FOR 6 MINS >	0	0	0	0
IF MICROBURST NOT CONFIRMED BY AN ENCOUNTER PIREP, SHOULD IT HAVE BEEN?	CONFIRMED	CONFIRMED	CONFIRMED	CONFIRMED	CONFIRMED	PROBABLY ⑤
TIMELINESS OF NCAR ADVISORY		⑥				
• FIRST ENCOUNTER	4 MIN EARLY	NOT APPLICABLE	5 MIN LATE	UNKNOWN	5 MIN LATE	-
• MAXIMUM STRENGTH ENCOUNTER	6 MIN EARLY	NOT APPLICABLE	4 MIN EARLY	UNKNOWN	2 MIN LATE	-

NOTES

① PROBABLE CAUSE FOR THE MISSED CP2 DETECTION - NCAR ATTENTION ON INTERMITTANT CP2 OPERATION DURING STARTUP OF SERVICE

② PROBABLE CAUSE FOR THE MISSED CP2 DETECTION - WEAK CLEAR AIR RADAR RETURN

③ PROBABLE CAUSE FOR THE MISSED CP2 DETECTION - OUTFLOW REMAINED BELOW THE RADAR SCAN

④ PIREP RECIEVED BY THE TRACON AT AN UNKNOWN TIME AND THEN RELAYED TO THE ATCT

⑤ MICROBURST MAY HAVE BEEN HELD ALOFT BY THE COLD SURFACE AIR OF A PRECEEDING GUST FRONT

⑥ DEPARTURES ALREADY DELAYING TAKEOFF DUE TO MICROBURST 7 WHEN ADVISORY RECEIVED

TABLE 3-2: SUMMARY OF MICROBURST CASES (continued)

	MICROBURST CASE NUMBER 13	14	15	16	17	18
DATE	7-21-84	7-25-84	7-25-84	7-27-84	7-30-84	7-30-84
NCAR ADVISORY						
• TIME ISSUED (LOCAL DENVER TIME)	7:32 PM	5:42 PM	5:42 PM	5:46 PM	5:04 PM	6:04 PM
• DIST. (NM) DIRECTION FROM CENTER FIELD	3 NW	5 NNW	4 WNW	2 N	4 SSE	2 W
• POTENTIAL MAXIMUM WIND SHEAR STRENGTH	30 KTS	50 KTS	50 KTS	40 KTS	50 KTS	50 KTS
• CP2 OPERATIONAL STATUS	UP	UP	UP	UP	UP	UP
• SOURCE OF ADVISORY	TOWER SIGHT ①	CP2	CP2	CP2	CP2	CP2
TIME OF FIRST FAA ANNOUNCEMENT OF ADVISORY	7:37 PM	NOT ISSUED	NOT ISSUED	5:46 PM	5:05 PM	6:05 PM
OPERATIONAL IMPACT OF MICROBURST (MB)						
• No OF ARRIVAL ENCOUNTER PIREPS	NONE	NONE	NONE	NONE	NONE	NONE
• No OF DEPARTURE ENCOUNTER PIREPS	NONE	NONE	NONE	NONE	NONE	NONE
• FIRST ENCOUNTER	-	-	-			-
• MAXIMUM STRENGTH ENCOUNTER	-	-		-	-	-
• EST. No OF AIRCRAFT THAT FLEW THROUGH MB	0	0	0	0	0	0
• No OF MISSED APPROACHES	NONE	NONE	NONE	NONE	NONE	NONE
• DURATION THAT DEPS DELAYED TAKEOFFS	0	0	0	1 MIN	0	0
IF MICROBURST NOT CONFIRMED BY AN ENCOUNTER PIREP, SHOULD IT HAVE BEEN?	NO	NO	NO	OBSERVED BUT NOT ENCOUNTERED	OBSERVED BUT NOT ENCOUNTERED	OBSERVED BUT NOT ENCOUNTERED
TIMELINESS OF NCAR ADVISORY						
• FIRST ENCOUNTER	-	-	-	-	-	-
• MAXIMUM STRENGTH ENCOUNTER	-	-	-	-	-	-

NOTES ① PROBABLE CAUSE FOR THE MISSED CP2 DETECTION - WEAK CLEAR AIR RADAR RETURN FROM STAPLETON DUE TO SHOWERS WASHING TRACERS OUT OF THE AIR

TABLE 3-2: SUMMARY OF MICROBURST CASES (continued)

	MICROBURST CASE NUMBER 19	20	21	22	23	24
DATE	8-1-84	8-4-84	8-4-84	8-5-84	8-5-84	8-5-84
NCAR ADVISORY	①					
• TIME ISSUED (LOCAL DENVER TIME)	4:00PM(4:08PM)	4:53 PM	5:14 PM	5:12 PM	5:13 PM	5:22 PM
• DIST. (NM) DIRECTION FROM CENTER FIELD	2N (5N)	6N	3N	5E	5SE	2 5SE
• POTENTIAL MAXIMUM WIND SHEAR STRENGTH	30 KTS (50KTS)	50 KTS	50 KTS	50 KTS	50 KTS	50 KTS
• CP2 OPERATIONAL STATUS	UP	UP	UP	UP	UP	UP
• SOURCE OF ADVISORY	CP2	CP2	CP2	CP2	CP2	CP2
TIME OF FIRST FAA ANNOUNCEMENT OF ADVISORY	4:03 PM	4:53 PM	5:17 PM	5:12 PM	NOT ISSUED	NOT ISSUED
OPERATIONAL IMPACT OF MICROBURST (MB)						
• No OF ARRIVAL ENCOUNTER PIREPS	NONE	4	NONE	1	NONE	NONE
• No OF DEPARTURE ENCOUNTER PIREPS	NONE	NONE	NONE	NONE	NONE	NONE
• FIRST ENCOUNTER		4:52 PM (GOOD SINKER)		5:12 PM (LT-MOD TURB)		-
• MAXIMUM STRENGTH ENCOUNTER	-	4:57 PM (-25 KTS)	-	SAME		-
• EST. No OF AIRCRAFT THAT FLEW THROUGH MB	0	4 ARRIVALS	0	1 ARRIVAL	0	0
• No OF MISSED APPROACHES	NONE	NONE	NONE	NONE	NONE	NONE
• DURATION THAT DEPS DELAYED TAKEOFFS	0	0	0	0	0	0
IF MICROBURST NOT CONFIRMED BY AN ENCOUNTER PIREP, SHOULD IT HAVE BEEN?	NO	CONFIRMED	NO	CONFIRMED	NO	NO
TIMELINESS OF NCAR ADVISORY						
• FIRST ENCOUNTER	-	1 MIN LATE	-	IN TIME	-	-
• MAXIMUM STRENGTH ENCOUNTER	-	4 MIN EARLY	-	IN TIME	-	-

NOTES ① A TRAVELING MICROBURST - TWO ADVISORIES ISSUED

TABLE 3-2: SUMMARY OF MICROBURST CASES (continued)

MICROBURST CASE NUMBER	25	26	27	28	29	30
DATE	8-5-84	8-12-84	8-12-84	8-12-84	8-15-84	8-15-84
NCAR ADVISORY	①	②				
• TIME ISSUED (LOCAL DENVER TIME)	5 51PM(6 00PM)	6.00PM(6 17PM)	6 38 PM	6 50 PM	3:38 PM	4:08 PM
• DIST. (NM) DIRECTION FROM CENTER FIELD	1N (4N)	ON AIRPORT (4E)	2 5 SE	5 5 N	1 SE	5 N
• POTENTIAL MAXIMUM WIND SHEAR STRENGTH	70 KTS (40KTS)	40 KTS (40KTS)	40 KTS	45 KTS	25 KTS	35 KTS
• CP2 OPERATIONAL STATUS	UP	UP	UP	UP	UP	UP
• SOURCE OF ADVISORY	CP2	LLWAS/PIREP ③	CP2	CP2	LLWAS ③	CP2
TIME OF FIRST FAA ANNOUNCEMENT OF ADVISORY	5.52 PM	6:01 PM	6 38 PM	6.51 PM	NOT ISSUED	4:09 PM
OPERATIONAL IMPACT OF MICROBURST (MB)						
• No OF ARRIVAL ENCOUNTER PIREPS	6	2	NONE	NONE	1	2
• No OF DEPARTURE ENCOUNTER PIREPS	NONE	NONE	NONE	NONE	NONE	NONE
• FIRST ENCOUNTER	5 58 PM (GOOD SHEAR)	5:57 PM (10 KTS)	-		3 28 PM (20 TO 25 KTS)	4 09 PM (5 TO 7 KTS)
• MAXIMUM STRENGTH ENCOUNTER	6:02 PM (+25-30 KTS)	6:01 PM (REAL SINKER)	-	-	SAME	SAME
• EST. No OF AIRCRAFT THAT FLEW THROUGH MB	16 ARRIVALS	3 ARRIVALS	0	0	1 ARRIVAL	3 ARRIVALS
• No OF MISSED APPROACHES	NONE	1	NONE	NONE	NONE	NONE
• DURATION THAT DEPS DELAYED TAKEOFFS	0	15 MINS	0	0 ④	0	0
IF MICROBURST NOT CONFIRMED BY AN ENCOUNTER PIREP, SHOULD IT HAVE BEEN?	CONFIRMED	CONFIRMED	NO	NO	CONFIRMED	CONFIRMED
TIMELINESS OF NCAR ADVISORY						
• FIRST ENCOUNTER	7 MIN EARLY	3 MIN LATE	-	-	<1 MIN LATE	1 MIN EARLY
• MAXIMUM STRENGTH ENCOUNTER	11 MIN EARLY	1 MIN EARLY	-	-	<1 MIN LATE	1 MIN EARLY

NOTES
① A TRAVELING MICROBURST - ADVISORY UPDATED TWICE; THE SECOND UPDATE SHOWN IN PARENTHESES
② A TRAVELING MICROBURST - ADVISORY UPDATED ONCE
③ PROBABLE CAUSE OF THE MISSED CP2 DETECTION - WEAK CLEAR AIR RADAR RETURN
④ DEPARTURES TURNED SHORTLY AFTER LIFTOFF TO AVOID THE MICROBURST AREA

TABLE 3-2: SUMMARY OF MICROBURST CASES (continued)

4) If the microburst was not confirmed by an encounter PIREP, should it have been based on its nearness to the runway operation? (If the answer is yes, the advisory was a false alarm.)

5) The timeliness of the NCAR advisory relative to both the first and maximum strength encounters.

The microburst case numbers number the microbursts in their order of occurrence.

Based on Table 3-2 one can make a number of observations concerning the microburst advisory service.

<u>Microburst Advisories were Issued by NCAR for 29 out of the 30 Observed Microbursts</u>

NCAR did not issue an advisory for Microburst 2. The probable cause of the missed advisory was saturation of the NCAR team. The missed microburst occurred during the first days of the six week operation and was accompanied by a gust front, a weak tornado and a second microburst. All four wind shear features occurred within the five nautical mile surveillance ring around Stapleton within a 15 minute period.

<u>After a Startup Period, the NCAR Meteorologists Using the CP-2 Achieved a Detection Rate of 80% for Stapleton Microbursts</u>

Given its poor siting relative to providing Stapleton microburst coverage (see Section 2), the CP-2 was still the source of advisories for 20 of the 30 microbursts. To account for startup, the CP-2 detection rate was calculated for each set of ten microbursts:

1) Microbursts 1 to 10 - the detection rate was 40%

2) Microbursts 11 to 20 - the detection rate was 80%

3) Microbursts 21 to 30 - the detection rate was 80%

In the post startup period, the CP-2 provided a detection rate of 80% for Stapleton microbursts.

A review of the daily logs maintained by NCAR during the project indicated that there were three probable causes for the ten missed CP-2 detections. In five cases, the logs noted that the CP-2 was receiving weak clear air return from Stapleton due to recent showers having washed tracers (i.e., insects, seeds, etc.) out of the air. This problem would have been lessened if the radar had been sited closer to Stapleton.

Although the CP-2 was operating during each of the 30 microburst episodes, there was a period at the start of the project in which the operational status of the CP-2 was intermittant. During this startup period, the NCAR meteorologists at the CP-2 divided their attention between the status of the CP-2 and monitoring the radar display. The inability of the NCAR meteorologists at the CP-2 site to devote their full attention to their primary task was noted as the probable cause of three missed CP-2 detections early in the project.

The third probable cause of missed CP-2 microburst detections was that the microburst outflow remained low and in the blocked portion of the CP-2 scan. This was noted as the probable cause for one missed CP-2 detection. This cause would have been eliminated if the radar was sited so its scan was not blocked by terrain in the direction of Stapleton.

Non-Doppler Weather Radar Sources Were Used by NCAR to Issue Advisories for the "Missed" CP-2 Microburst Detections

In an attempt to catch missed radar microburst detections, the two NCAR meteorologists in the ATCT monitored: (i) the scene around the airport for visual cues of blowing dust caught up in a microburst's overflow and (ii) the LLWAS for indications of a possible microburst outflow on the airport's surface. NCAR issued advisories for:

1) Five microbursts based on visual sightings,

2) Two microbursts based on the LLWAS,

3) One microburst based on a PIREP,

4) One microburst based on both the LLWAS and a PIREP.

The Doppler Radar Based Microburst Advisories Were Timely and Preceeded the First Encounter PIREPs by an Average of Two Minutes

Five CP-2 based microburst advisories had associated encounter PIREPs. To gauge the timeliness of the NCAR advisories, the time of issuance of the advisory was compared with both the time of the: (i) first PIREP reporting an encounter with the microburst and (ii) maximum strength encounter PIREP. The results of this comparison for the CP-2 based advisories are:

1) The first encounter PIREP - the advisories ranged from being one minute late to seven minutes early and averaged two minutes early.

2) The maximum strength encounter PIREP - the advisories ranged from being one minute early to eleven minutes early and averaged four minutes early.

The Microburst Advisories Based on Visual Sightings were Less Timely But Still Preceeded the Maximum Strength Encounter PIREPs by Two Minutes on Average

Three microburst advisories based on visual sightings had associated encounter PIREPs. In contrast to the CP-2 based advisories, all three of these visual based advisories were late relative to the first encounter PIREP (i.e.; ranged from 2 to 5 minutes late and averaged 3 minutes late). However, the advisories were still of potential operational value because they tended to be early relative to the maximum strength encounter PIREP (i.e., ranged from 2 minutes late to 5 minutes early and averaged 2 minutes early).

The Microburst Advisories Based on the LLWAS Were of Marginal Timeliness

The two LLWAS based advisories, which could be compared with pilot reports, show that they were issued very close to the time that the maximum strength PIREP was being received in each case.

The FAA Passed-On the NCAR Advisories to Pilots on a Selective Basis

The FAA passed on the NCAR advisories for 19 microbursts and witheld the advisories for 10 microbursts. Table 3-2 shows that advisories were withheld for two reasons - either the microburst was considered clear of the runway operation or wind shear PIREPs were already being received from the area of the microburst.

For those advisories that were passed on, the lapsed time between the issuance of the advisory by NCAR and the first announcement of the advisory to pilots by local control was typically a minute or less for microbursts in close proximity to the runway operation.

3.3 THE OPERATIONAL IMPACT OF MICROBURSTS ON ARRIVALS - THE SIX WEEK RECORD

To put the following discussion into perspective, it should be noted that the microbursts encountered during the six week operating period were all of moderate strength or less. In earlier studies of Denver microbursts, NCAR found that the wind differential across a microburst's outflow, when it had built up to maximum strength (see Table 3-1):

1) Averaged 49 kts

2) Could be as high as 93 kts.

Based on PIREPs from pilots that flew through both sides of a microburst's outflow during the project, the maximum wind differential reported per microburst ranged from 35 to 60 kts and averaged 48 kts (Table 3-2). The microbursts encountered were well below the 93 kt NCAR maximum but closely agreed with the NCAR average.

Table 3-2 presents the record of the microburst impact on Stapleton arrival operations over the six week operating period. The record shows that:

1) Pilots on final approach reported encountering 12 of the 30 microbursts detected.

2) The number of pilot encounter reports received per microburst ranged from one to nine and averaged four.

3) The estimated number of arrivals that flew through each microburst and landed ranged from one to 16 and averaged six.

4) Three microbursts caused a total of four pilots to execute missed approaches.

5) These same three microbursts were encountered by an estimated total of 23 pilots which continued their approaches and landed.

The six week operating period provided a sample of pilot reports of and pilot reaction to microburst encounters on final approach that is large enough to permit one to start to define the area of microburst locations of concern to landing pilots.

The most critical microburst center location for arrivals is the last mile of final approach where pilots will tend to experience changing wind conditions all the way to touchdown. Before CLAWS, it was known from Dr. Theodore Fujita's work that at least two microburst related accidents, involving landing aircraft, occurred in the United States between 1975 and 1979 (Reference 3-1) - the:

1) B-727 accident at Kennedy International Airport on June 24, 1975 involving 112 fatalities and 12 injuries,

2) DC-9 accident of Philadelphia International Airport on June 23, 1976 involving 106 injuries and no fatalities.

Both aircraft encountered a microburst centered a little over a half nautical mile prior to reaching the runway.

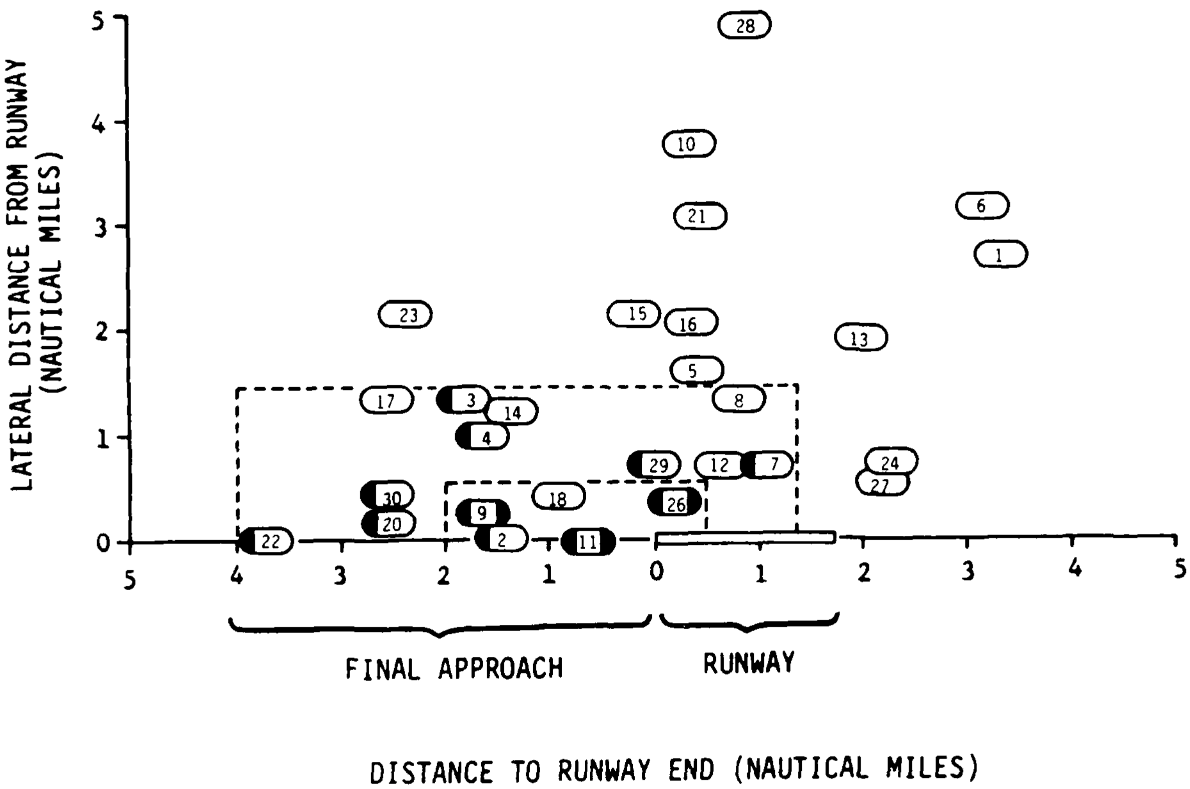
Figure 3-5 shows the locations of the microburst centers that occurred during the six week operating period as reported by NCAR. The microburst centers are shown relative to the closest arrival runway in operation at the time. It is seen that Microburst 11 was centered in the critical last mile of final approach and resulted in one or more missed approaches. A second microburst, not shown in this figure (i.e., the travelling microburst presented in Figure 3-4), resulted in no missed approaches but caused one pilot that encountered the microburst in this critical area to comment later "... we were a heavily loaded 737 in the critical approach phase and this warning in advance (i.e., the microburst advisory) may have just saved an aircraft from being forced into the ground short of the runway."

Figure 3-5 shows that, for this sample, the area of concern relative to potential missed approaches involved microbursts centered from about 2 nautical mile final to about .5 nautical miles down the arrival runway. Three microbursts in that area prompted 4 out of 27 pilots to execute missed approaches:

1) Microburst 9 (centered in the vicinity of 1.5 nautical mile final) - the fourth and eighth aircraft to encounter the microburst executed missed approaches with the comments "20 kt loss ... going around" and "$\pm$ 30 kts ... full power and could not climb ... going around."

2) Microburst 11 (centered in the vicinity of .5 nautical mile final) - the third aircraft after the first encounter initiated a missed approach on hearing a PIREP from the preceeding flight "severe wind shear and lost 30 kts."

3) Microburst 26 (started at the approach end of the arrival runway and traveled down the runway away from the final approach path) - the fourth aircraft after the first encounter initiated a missed approach before encountering the microburst with the comment "Going around ... don't want to go into that thing."



LEGEND

(17) LOCATION OF A MICROBURST CENTER AS REPORTED BY NCAR PLUS THE MICROBURST IDENTIFICATION NUMBER (SEE TABLE 3-2)

(22) LOCAL CONTROL RECEIVED MICROBURST ENCOUNTER PIREPS

(11) IN ADDITION TO PIREPS THE MICROBURST CAUSED ONE OR MORE PILOTS TO EXECUTE A MISSED APPROACH

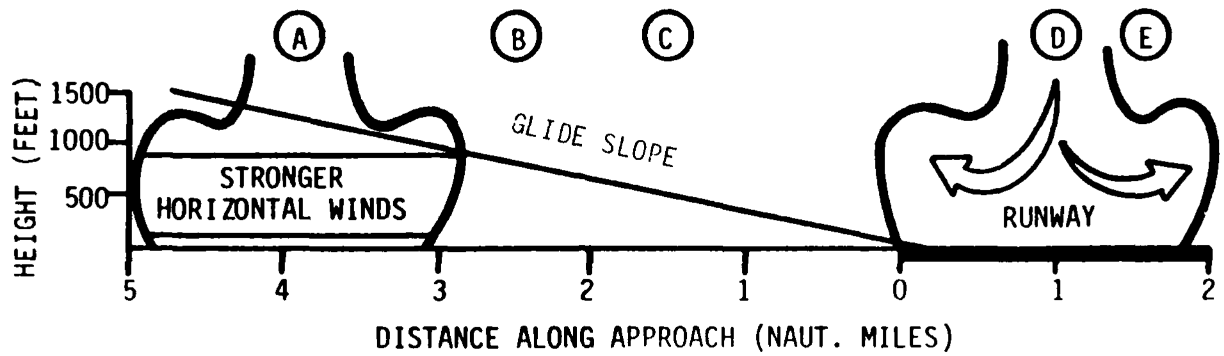
FIGURE 3-5: MICROBURST IMPACT ON ARRIVAL OPERATIONS OVER THE SIX WEEK OPERATING PERIOD

It is seen that Microbursts 12 and 18 were close to this area but were not encountered. Microburst 18 was observed by both pilots and the local controller and was described as a small feature just to one side of the final approach path. As noted in the daily NCAR logs, Microburst 12 was preceeded by a gust front that caused a drop in the surface temperature at Stapleton. It is possible that Microburst 12 never reached the ground but remained aloft due to this layer of cold surface air (see Table 3-1). Due to the blocked CP-2 beam below 850 feet above the airport, a microburst held aloft by a cold cushion of surface air would look the same as a microburst reaching ground level.

Figure 3-5 shows two zones of concern to landing pilots. The smaller dashed box represents the microburst center locations that caused missed approaches. The larger dashed box represents those microburst center locations that resulted in pilot reports of microburst encounters.

Figure 3-6 presents the type of pilot report normally received by the control tower versus microburst center location along the approach path. For microbursts with center locations between 3.5 nautical mile final and 1.5 nautical miles down the arrival runway, pilots encounter some part of the microburst's outflow and tend to report encountering wind shear. Microbursts located further down the runway are of no direct operational concern because the outflow winds are not encountered until after touchdown. Microbursts located further out than 3.5 nautical mile final are of reduced operational concern because the aircraft are above the stronger horizontal winds of the outflow and have at least a 1000 ft. altitude cushion. Pilots encountering microbursts at these altitudes may report experiencing light to moderate turbulence and/or some loss in altitude.

In support of these findings, partway through the project NCAR and the FAA found it useful to extend the initial 2.5 nautical mile coverage on Runway 17L final out to 3.5 nautical miles. This resulted in advisories being issued for microbursts out to 6, versus 5, nautical miles north of Stapleton center field. This explains the Microburst 20 and 28 entries in Table 3-2.



MB CENTER LOCATION	WINDS ENCOUNTERED	EXAMPLE PIREPS (MICROBURST NUMBER)
A	DF	"LIGHT TO MODERATE TURBULENCE" (MB 22)
B	DF/TW	"PRETTY GOOD SINKER ... 20 TO 30 KT TAIL WIND AT 500 FT" (MB 20)
C	HW/DF/TW	" ± 30 KTS ... FULL POWER AND COULD NOT CLIMB" (MB 9)
D	HW	" + 20 KTS AT ABOUT 100 FT" (MB 7)
E	HW AFTER TOUCHDOWN	NO PIREPS EXPECTED

NOTATION: MICROBURST (MB), DOWNFLOW (DF), HEADWIND (HW), TAILWIND (TW)

FIGURE 3-6: TYPE OF PIREP VERSUS MICROBURST LOCATION ALONG THE APPROACH PATH

Figure 3-7 summarizes the operational impact of microburst center location for landing aircraft. The microburst outline is shown in the most sensitive microburst location for landing aircraft.

These results should be considered preliminary in that: (i) they are based on a small number of microburst case studies at a single airport and (ii) the microburst locations used in the sample are approximations. NCAR is of the opinion that the microburst center locations stated in the CP-2 based advisories were typically within .5 km of their true locations at the time the advisories were issued. After an advisory was issued, the center of a microburst could move as far as 2 km or more during its lifetime but typically moved very little. Consequently, the preceeding discussion of the impact of microburst location on landing operations should be viewed as a starting point to be refined as additional data becomes available in the future.

3.4 THE OPERATIONAL IMPACT OF MICROBURSTS ON DEPARTURES - THE SIX WEEK RECORD

A similar analysis can be made for departure operations. Figure 3-8 presents a plan view of the microburst center locations shown relative to the closest departure runway in operation at the time over the six week period. Unfortunately from an analysis viewpoint, far fewer microbursts had an effect on departure operations than was the case for arrivals. Departures were affected by five out of the 30 microbursts. Brief descriptions of these episodes follow:

1) Microburst 7 was encountered by two departures before pilots started to delay their takeoffs due to LLWAS readings showing cross winds in excess of the 20 kt threshold. Microburst 8 hit the same departure runway shortly after the last departure took off. Pilots delayed their takeoffs for six minutes, until the LLWAS readings showed the cross winds to be below 20 kts.

2) Microburst 10 was encountered by at least one pilot who reported difficulty with the takeoff climb,

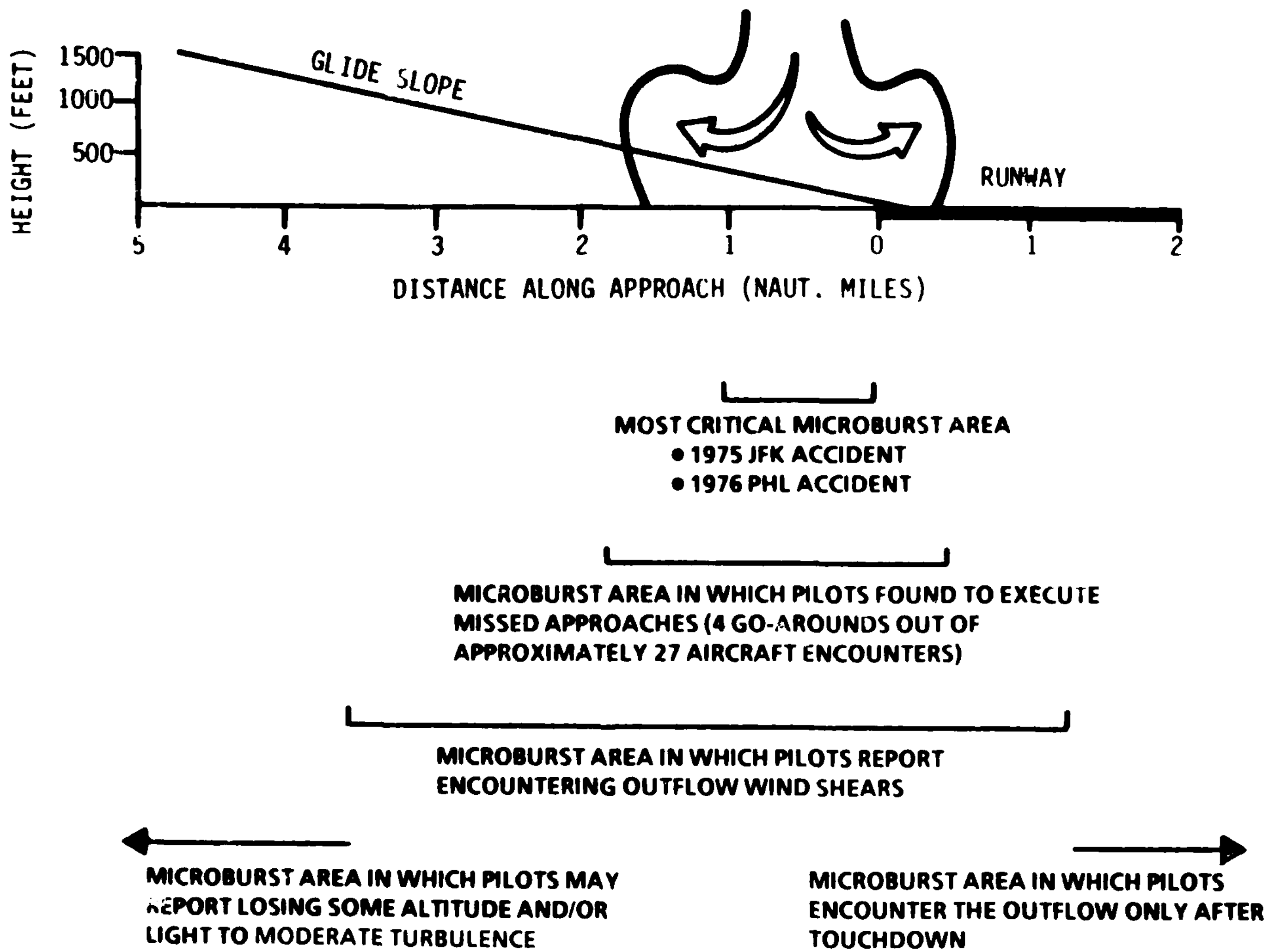
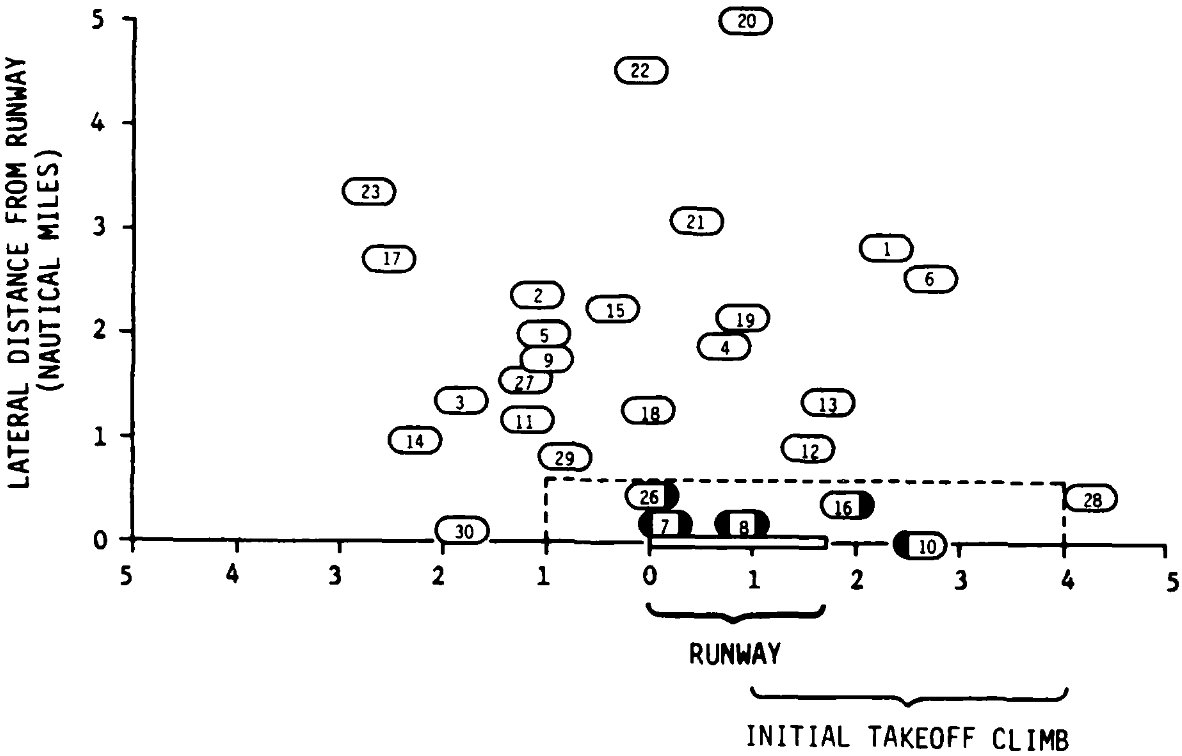


FIGURE 3-7: OPERATIONAL IMPACT OF MICROBURST CENTER LOCATION FOR ARRIVALS (PRELIMINARY)



LEGEND

(30) LOCATION OF A MICROBURST CENTER AS REPORTED BY NCAR PLUS THE MICROBURST IDENTIFICATION NUMBER (SEE TABLE 3-2)

(10) LOCAL CONTROL RECEIVED MICROBURST ENCOUNTER PIREPS

(16) THE MICROBURST CAUSED ONE OR MORE PILOTS TO DELAY THEIR TAKE OFFS

FIGURE 3-8: MICROBURST IMPACT ON DEPARTURE OPERATIONS OVER THE SIX WEEK OPERATING PERIOD

3) Microburst 26 kept departures delaying their takeoffs after a gust front passage. The departures stayed on the ground the first seven minutes of the microburst advisory due to LLWAS readings showing that cross winds in excess of the 20 kt threshold were present. The advisory kept the departures on the ground for an additional 13 minutes when the departure runway cross winds were below 20 kts. Departure operations started when NCAR advised the controllers, who in turn advised the waiting pilots, that the microburst had moved to a position four nautical miles to one side of the departure runways. Microburst 26 was one of three travelling microbusts observed during the project.

These episodes illustrate a number of points. First, they show how departing pilots key on the LLWAS to make their evaluation as to whether wind conditions on the runway warrant a delay in takeoff. Second, these episodes show that the advisories were being used by some departing pilots to supplement the LLWAS information by the time of Microburst 26, if not before. Third, Microburst 26 shows the importance of accurately defining the area of operational concern relative to microbursts for departing pilots. NCAR had no fixed policy for updating advisory position for travelling microbursts. The Microburst 26 position was not updated until it was well outside the area of operational concern. Fourth, delayed takeoffs due to a microburst on the departure runway ranged from one to seven minutes during the project and averaged about four minutes.

The dashed box in Figure 3-8 shows the area of microburst,center locations of concern to departing pilots as reported to the control tower in this sample. Pilots tended to delay their takeoffs for short periods for microbursts centered anywhere along the runway.

To determine the most hazardous zone of microburst locations for departures, one can refer to Dr. Fujita's body of work concerning microburst related aircraft accidents.

Dr. Fujita has found that at least two such accidents involving aircraft during takeoff have occurred in the United States since 1975 (Reference 3-2) - the:

1) B-727 accident at Stapleton International Airport on August 7, 1975 involving 15 injuries and no fatalities,

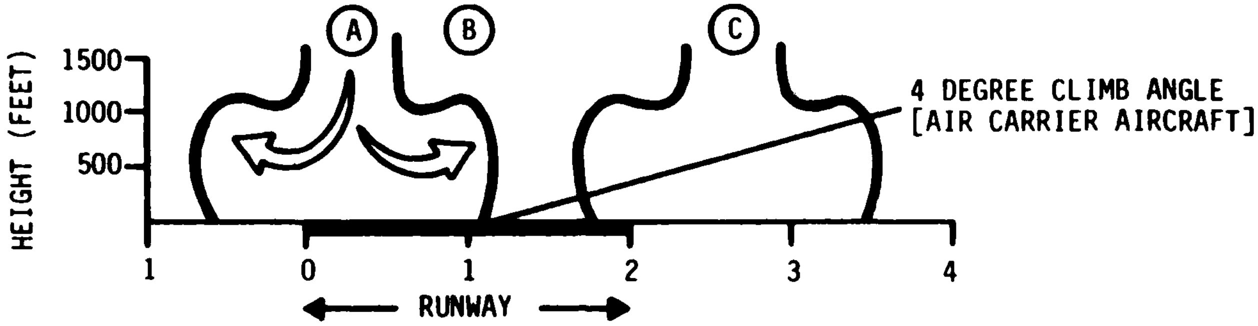
2) B-727 accident at New Orleans International Airport on July 9, 1982 involving 9 injuries and 153 fatalities.

Both aircraft encountered a microburst centered approximately 8000 feet down the runway (References 3-3 and 3-4) - just after the area where aircarrier aircraft normally lift off.

Figure 3-8 shows that Microburst 8 was located near this critical location, but the microburst was not encountered until it was dissipating. Fortunately, Microburst 7 had caused pilots to start to delay their takeoffs prior to Microburst 8 hitting the runway.

Figure 3-9 presents examples of the type of PIREPs received at Stapleton versus microburst center location for departures. As one would expect, microburst encounters are described by departing pilots quite differently than by landing pilots. A microburst centered over the roll initiation end of the runway causes pilots to experience difficulty with their takeoff roll (i.e., pilots may need to use more runway than usual during takeoff roll to achieve liftoff airspeed), while a microburst centered over the departure end of the runway causes pilots to experience difficulty with their initial takeoff climb. A microburst located between the two ends of the departure runway can cause pilots to experience difficulty with takeoff roll, liftoff and initial climb.

Figure 3-10 summarizes the operational impact of microburst location for departing aircraft. The microburst outline is shown at the most sensitive microburst location for departing aircarrier aircraft (i.e., the area in or near the normal liftoff portion of the runway).



MB CENTER LOCATION	WINDS ENCOUNTERED	EXAMPLE PIREPS (MICROBURST NUMBER)
A	DF/TW	"SQUIRRELLY AT ROTATION ... + 15 KTS OVER DEPARTURE END" (MB7) "HAD STAGNATION FOR 500 TO 700 FEET BEFORE AIRSPEED INCREASED"
B	HW/DF/TW	"AT 90 KTS AIRSPEED HUNG BOUNCED TO 100 KTS AND HUNG AGAIN ... PUSHED THROTTLES FULL FORWARD"
C	HW/DF	REPORT OF DIFFICULTY IN CLIMB (MB10)

NOTATION: MICROBURST (MB), DOWNFLOW (DF), HEADWIND (HW), TAILWIND (TW)

FIGURE 3-9: TYPE OF PIREP VERSUS MICROBURST LOCATION ALONG DEPARTURE PATH

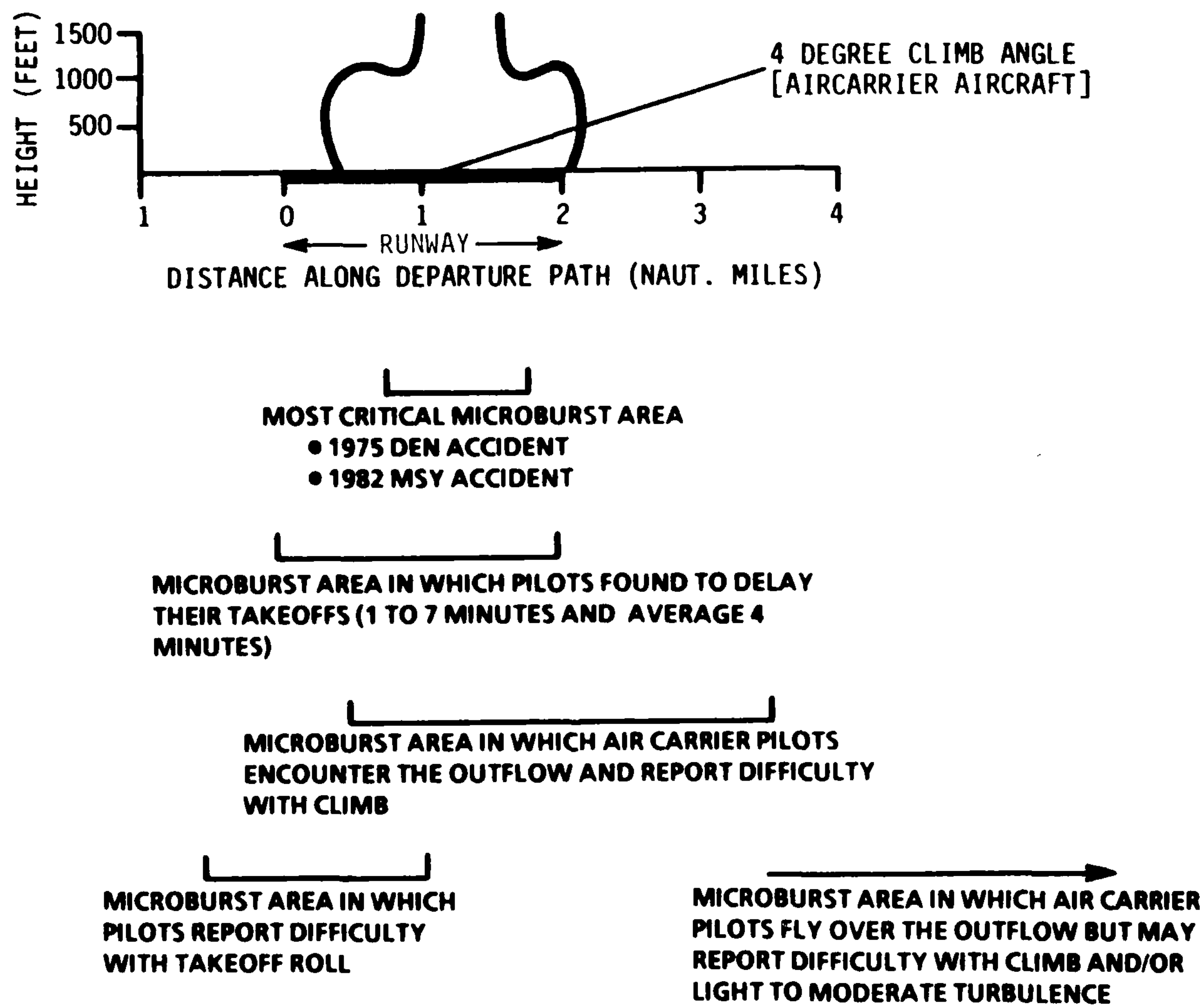


FIGURE 3-10: OPERATIONAL IMPACT OF MICROBURST CENTER LOCATION FOR DEPARTURES (PRELIMINARY)

4. AN INFORMAL GUST FRONT ADVISORY SERVICE

Early in the six week operating period, the NCAR radar meteorologists noticed that they could clearly see gust fronts and other wind shift lines approaching and passing over Stapleton. After some experimentation, NCAR initiated an informal "gust front" advisory service for these wind shift lines.

NCAR would verbally advise the watch supervisor in the ATCT of the expected time of arrival of the wind shift line at the Stapleton LLWAS center field sensor and its estimated maximum wind strength and wind direction. These wind shift lines can make it necessary to shift the runways in operation so that landing and departing aircraft continue to operate into the wind with acceptable crosswinds. The watch supervisor is responsible for planning and timing these runway changes.

These advisories were informal in that each watch supervisor was free to ignore, test, or use the advisories. After a confidence building period in which the advisories were informally evaluated by the watch supervisors, the advisories began to be used operationally. The use of these advisories was solely for runway management purposes. They were not used to advise landing and departing pilots of potential wind shear encounters, which was beyond the resources of the project.

This section presents: (1) a partial record of the advisory service over the six week operating period and (2) the results of exploratory discussions with Stapleton ATC personnel concerning the operational impact of wind shift lines and the potential role/benefit of these advisories for runway management purposes.

4.1 THE GUST FRONT ADVISORY SERVICE - A PARTIAL SIX WEEK RECORD

NCAR issued advisories for nearly 30 of the 32 wind shift lines observed nearing Stapleton over the six week operation. An unknown number of these advisories were used in support of operations.

The data set collected for these advisories is incomplete for two reasons. First, the informal nature of the service, in itself, led to a minimum of formal record keeping in the field. Second, the focus of the limited resources available for the project was directed to providing the best microburst advisory service possible and to documenting the results of that service.

ATC data (i.e., local control communication tapes) were collected for 14 wind shift lines of which 12 had advisories. Table 4-1 presents the operational impact of these 14 lines (i.e., the number of missed approaches caused and whether or not a runway change was made) and the timeliness and accuracy of the advisories. The table shows that the advisories tended to be timely and accurate:

1) Advisory lead time ranged from 3 to 50 minutes and averaged 17 minutes, (This reflects an Air Traffic request for 20 minute lead times; NCAR personnel felt that they had the capability of providing significantly longer lead times.)

2) Estimated time of arrival accuracy ranged from perfect to as much as 10 minutes off with an average error of 4 minutes (The time of arrival was measured from the start in the shift in wind direction at the center field LLWAS sensor.),

3) Estimated maximum wind strength accuracy ranged from perfect to as much as 19 kts. off with an average error of 7 kts. (Wind strength was measured at the center field LLWAS sensor.),

4) Estimated final wind direction was accurate for 70 percent of the advisories (ie., within $\pm$ 25 degrees of the actual wind direction; wind direction tended to be issued as N, NW, W, etc. with a 45 degree quantization) and was in error between 35 and 95 degrees for 30 percent of the advisories.

After the test was completed, the consensus of opinion among the Stapleton watch supervisors was that:

1) Planning runway changes due to wind shift lines was much more efficient with the advisories.

	WIND SHIFT LINE CASE NUMBER 1	2	3	4	5
DATE	7-6-84	7-7-84	7-15-84	7-20-84	7-20-84
NCAR ADVISORY					
• TIME ISSUED (LOCAL DENVER TIME)	NONE ISSUED	NONE ISSUED	2:22 PM	3:48 PM	6:40 PM
• ESTIMATED TIME OF ARRIVAL AT CENTER FIELD			2:25 PM	3:55 PM	6:55 PM
• ESTIMATED MAXIMUM WIND STRENGTH			40 KTS.	25 KTS.	20 TO 25 KTS
• ESTIMATED FINAL WIND DIRECTION (1)			NW	S	NNW
WIND SHIFT LINE AT CTR. FIELD LLWAS SENSOR					
• ACTUAL TIME OF ARRIVAL (2)	2:25 PM	3:20 PM	<2:25 PM	3:55 PM	6:47 PM
• ACTUAL MAXIMUM WIND STRENGTH (3) (5)	32 (G47) KTS	10 KTS	11 (G21) KTS	28 (G40) KTS	15 (G21) KTS
• ACTUAL FINAL WIND DIRECTION (3)	180 DEG.	270 DEG.	260 DEG.	180 DEG.	350 DEG
ADVISORY PERFORMANCE					
• LEAD TIME	NOT APPLICABLE	NOT APPLICABLE	UNKNOWN	7 MIN	7 MIN.
• TIME OF ARRIVAL ERROR			UNKNOWN	NONE	8 MIN.
• MAXIMUM STRENGTH ERROR			19 KTS. HIGH	15 KTS	NONE
• FINAL DIRECTION ERROR (4)			55 DEG	NONE	NONE
OPERATIONAL IMPACT OF LINE					
• NUMBER OF MISSED APPROACHES	3	0	0	1	0
• CAUSE A RUNWAY SHIFT?	YES	YES	NO	YES	YES

NOTES

(1) DIRECTION ESTIMATES TEND TO HAVE A 45 DEGREE QUANTIZATION

(2) TIME OF ARRIVAL TAKEN AT START OF WIND SHIFT AT CENTER FIELD LLWAS SENSOR

(3) AS MEASURED ON STAPLETON'S CENTER FIELD LLWAS SENSOR

(4) DUE TO QUANTIZATION, IF ESTIMATED WIND DIRECTION WAS WITHIN ± 25 DEGREES OF THE ACTUAL FINAL WIND DIRECTION, IT WAS ASSUMED THAT THERE WAS NO WIND DIRECTION ERROR

(5) AVERAGE WIND SPEED (GUST WIND SPEED)

TABLE 4-1: SUMMARY OF WIND SHIFT LINE CASES

	WIND SHIFT LINE CASE NUMBER 6	7	8	9	10
DATE	7-21-84	7-24-84	7-27-84	8-1-84	8-3-84
NCAR ADVISORY					
• TIME ISSUED (LOCAL DENVER TIME)	5:25 PM	3:32 PM	5:30 PM	2:35 PM	6:15 PM
• ESTIMATED TIME OF ARRIVAL AT CENTER FIELD	5:55 PM	3:42 PM	5:45 PM	2:50 PM	7:03 PM
• ESTIMATED MAXIMUM WIND STRENGTH	20 TO 25 KTS.	30 KTS.	NO EST.	20 KTS.	15 TO 20 KTS
• ESTIMATED FINAL WIND DIRECTION ①	NW	W	SE	SE	N
WIND SHIFT LINE AT CTR. FIELD LLWAS SENSOR					
• ACTUAL TIME OF ARRIVAL ②	5:48 PM	3:47 PM	5:46 PM	2:47 PM	7:05 PM
• ACTUAL MAXIMUM WIND STRENGTH ③ ⑤	12 (G22) KTS	23 (G35) KTS	23 (G33) KTS	17 KTS	18 KTS
• ACTUAL FINAL WIND DIRECTION ③	280 DEG.	260 DEG.	040 DEG	120 DEG	360 DEG
ADVISORY PERFORMANCE					
• LEAD TIME	23 MIN	15 MIN	16 MIN	12 MIN	50 MIN
• TIME OF ARRIVAL ERROR	7 MIN	5 MIN	1 MIN	3 MIN	2 MIN
• MAXIMUM STRENGTH ERROR	NONE	5 KTS	-	3 KTS	NONE
• FINAL DIRECTION ERROR ④	35 DEG	NONE	95 DEG	NONE	NONE
OPERATIONAL IMPACT OF LINE					
• NUMBER OF MISSED APPROACHES	1	1	3	0	0
• CAUSE A RUNWAY SHIFT?	YES	YES	YES	YES	NO

NOTES
① DIRECTION ESTIMATES TEND TO HAVE A 45 DEGREE QUANTIZATION
② TIME OF ARRIVAL TAKEN AT START OF WIND SHIFT AT CENTER FIELD LLWAS SENSOR
③ AS MEASURED ON STAPLETON'S CENTER FIELD LLWAS SENSOR
④ DUE TO QUANTIZATION, IF ESTIMATED WIND DIRECTION WAS WITHIN ± 25 DEGREES OF THE ACTUAL FINAL WIND DIRECTION, IT WAS ASSUMED THAT THERE WAS NO WIND DIRECTION ERROR
⑤ AVERAGE WIND SPEED (GUST WIND SPEED)

TABLE 4-1: SUMMARY OF WIND SHIFT LINE CASES (continued)

	WIND SHIFT LINE CASE NUMBER 11	12	13	14
DATE	8-4-84	8-5-84	8-12-84	8-14-84
NCAR ADVISORY				
• TIME ISSUED (LOCAL DENVER TIME)	3:58 PM	5:07 PM	5:08 PM	2:48 PM
• ESTIMATED TIME OF ARRIVAL AT CENTER FIELD	4:13 PM	5:17 PM	5:18 PM	3:28 PM
• ESTIMATED MAXIMUM WIND STRENGTH	< 10 KTS.	NO EST.	25 KTS.	25 KTS.
• ESTIMATED FINAL WIND DIRECTION ①	S	E	NE	NW
WIND SHIFT LINE AT CTR. FIELD LLWAS SENSOR				
• ACTUAL TIME OF ARRIVAL ②	4:03 PM	5:10 PM	5:21 PM	3:28 PM
• ACTUAL MAXIMUM WIND STRENGTH ③ ⑤	20 KTS.	16 KTS.	26 (G37) KTS.	19 KTS.
• ACTUAL FINAL WIND DIRECTION ③	180 DEG.	110 DEG.	90 DEG.	320 DEG.
ADVISORY PERFORMANCE				
• LEAD TIME	5 MIN.	3 MIN.	13 MIN	40 MIN.
• TIME OF ARRIVAL ERROR	10 MIN.	7 MIN.	3 MIN	NONE
• MAXIMUM STRENGTH ERROR	10 KTS.	-	12 KTS	6 KTS.
• FINAL DIRECTION ERROR ④	NONE	NONE	45 DEG.	NONE
OPERATIONAL IMPACT OF LINE				
• NUMBER OF MISSED APPROACHES	0	0	1	0
• CAUSE A RUNWAY SHIFT?	YES	YES	YES	NO

NOTES
① DIRECTION ESTIMATES TEND TO HAVE A 45 DEGREE QUANTIZATION

② TIME OF ARRIVAL TAKEN AT START OF WIND SHIFT AT CENTER FIELD LLWAS SENSOR

③ AS MEASURED ON STAPLETON'S CENTER FIELD LLWAS SENSOR

④ DUE TO QUANTIZATION, IF ESTIMATED WIND DIRECTION WAS WITHIN ± 25 DEGREES OF THE ACTUAL FINAL WIND DIRECTION, IT WAS ASSUMED THAT THERE WAS NO WIND DIRECTION ERROR

⑤ AVERAGE WIND SPEED (GUST WIND SPEED)

TABLE 4-1: SUMMARY OF WIND SHIFT LINE CASES (continued)

2) These advisories proved to be the greatest benefit of the project from an air traffic management standpoint.

The collected data set is insufficient to examine how these advisories actually do increase the efficiency of wind-shift-line-related runway changes or to measure their actual operational benefit.

As an alternative, these two issues were explored in brief discussions with three of the watch supervisors that used the advisories operationally during the project.

4.2 THE POTENTIAL ANNUAL BENEFIT OF THE GUST FRONT ADVISORY SERVICE - DISCUSSIONS WITH STAPLETON ATC PERSONNEL

Today, the watch supervisor in the ATCT uses the LLWAS sensors, PIREPs of wind shear encounters, weather reports, etc., in planning and timing runway changes due to wind shift features reaching the airport. These sources of wind information provide the watch supervisor with a very limited "picture" of the wind features in the vicinity of the airport.

During the project, the watch supervisors found that the gust front advisories provided a relatively clear, timely, and reliable picture of approaching wind shift lines. These advisories greatly aided in both the planning and timing of these runway shifts (i.e., selecting the new runway configuration and determining when the shift should be started). With these advisories, the watch supervisors found/believe that they can:

1) Move traffic into place on the new runway configuration in anticipation of the arrival of a wind shift line, which is not currently done (consequently, reducing traffic disruption and increasing runway utilization during these runway shifts).

2) Reduce/eliminate the need for a second runway shift due to the incorrect selection of the appropriate runway configuration the first time. (Operationally, this situation is sometimes called "chasing the winds.")

3) Reduce/eliminate unnecessary runway shifts in which the watch supervisor finds out after the fact that the actual wind conditions did not warrant a runway change (e.g., the anticipated wind strength that led to the runway shift either did not occur or was of such short duration as to have been of no operational consequence).

Elimination of these three problems would give one an estimate of the maximum potential annual savings that can be attributed to a Doppler based runway management product. To make this calculation, one must determine the average potential cost savings per incident for each of the three runway shift problems and the typical number of times each occurs during the course of a year at each airport of interest.

First-cut estimates of these values were obtained for Stapleton based on the experience of the three watch supervisors interviewed. The values presented are an average of those given by the supervisors.

Table 4-2 presents the estimated number of runway shifts that typically occur during the course of a year for each of the three runway situations. The year is divided into two parts - the primary thunderstorm season at Denver (i.e., June, July and August) and the other nine months of the year.

Table 4-3 presents the estimated potential cost savings per incident due to improved timing for a typical traffic situation. Table 4-4 presents the component values used in the estimate.

Finally, Table 4-5 presents the estimated annual potential cost savings for Stapleton that could be attributed to a Doppler radar based runway management product. The estimated annual savings is for $875K (1984 dollars).

Four points should be emphasized before concluding this section:

1) The enthusiastic response of the Stapleton watch supervisors to an unplanned product (i.e. the Gust Front Advisory) provided the basis on which the operational benefits of a Doppler radar based runway management product could be briefly explored.

	ESTIMATED NUMBER OF RUNWAY SHIFTS				
	THUNDERSTORM SEASON (3 MOS)		OTHER NINE MONTHS		
CURRENT PROBLEM	AVERAGE RATE OF OCCURRENCE	TOTAL FOR SEASON	AVERAGE RATE OF OCCURRENCE	TOTAL FOR SEASON	TOTAL FOR YEAR
CORRECT RUNWAY SHIFT BUT TIMING COULD BE IMPROVED	ONCE EVERY 1 TO 2 DAYS	75	ONCE EVERY 2 WEEKS	20	95
EXTRA RUNWAY SHIFT (1ST SHIFT NOT ALIGNED WITH WINDS - 2ND SHIFT NECESSARY)	ONCE EVERY 2 DAYS	45	ONCE EVERY 2 TO 3 WEEKS	15	60
EXTRA RUNWAY SHIFT (RUNWAY SHIFT MADE THAT PROVED TO BE UNNECESSARY WHEN THE WINDS BECAME KNOWN)	ONCE EVERY 2 TO 3 DAYS	40	ONCE EVERY 6 WEEKS	5	45

TABLE 4-2: ESTIMATED NUMBER OF STAPLETON RUNWAY SHIFTS PER YEAR THAT WOULD BE AIDED BY A DOPPLER RADAR BASED RUNWAY MANAGEMENT PRODUCT

SITUATION 1

WIND CONDITIONS ARE SUCH THAT THE REMAINING OPERATIONS IN QUEUE FOR OLD RUNWAY CONFIGURATION MUST PROCEED TO NEW RUNWAY CONFIGURATION (<u>ASSUMPTION</u> - OCCURS ONE OUT OF EVERY THREE RUNWAY SHIFTS)

$$\underbrace{[10\ DEPARTURES][\frac{8\ MIN.}{DEP.}][\frac{\$30}{MIN.}]}_{\text{DEPARTURE SAVINGS}}+\underbrace{[12\ ARRIVALS][\frac{8\ MIN.}{ARR.}][\frac{\$50}{MIN.}]}_{\text{ARRIVAL SAVINGS}}=\$7.2K\ PER\ INCIDENT$$

SITUATION 2

WIND CONDITIONS ARE SUCH THAT THE REMAINING OPERATIONS IN QUEUE FOR OLD RUNWAY CONFIGURATION CAN CONTINUE TO USE THAT CONFIGURATION BUT LACK OF LOW ALTITUDE WIND INFORMATION STILL RESULTS IN TWO LOST ARRIVAL AND DEPARTURE RUNWAY SLOTS (<u>ASSUMPTION</u> - OCCURS TWO OUT OF EVERY THREE RUNWAY SHIFTS)

$$\underbrace{[10\ DEPARTURES][\frac{4\ MIN.}{DEP.}][\frac{\$30}{MIN.}]}_{\text{DEPARTURE SAVINGS}}+\underbrace{[12\ ARRIVALS][\frac{3\ MIN.}{ARR.}][\frac{\$50}{MIN.}]}_{\text{ARRIVAL SAVINGS}}=\$3.0K\ PER\ INCIDENT$$

TABLE 4-3: ESTIMATED POTENTIAL COST SAVINGS PER RUNWAY SHIFT DUE TO IMPROVED TIMING INFORMATION PROVIDED BY A DOPPLER RADAR BASED RUNWAY MANAGEMENT PRODUCT

TYPICAL DEMAND	
NUMBER OF DEPARTURES IN QUEUE FOR DEPARTURE RUNWAYS	10 DEPARTURES
NUMBER OF ARRIVALS IN QUEUE FOR ARRIVAL RUNWAYS	12 ARRIVALS
TYPICAL DELAY PER OPERATION	
WIND CONDITIONS ARE SUCH THAT THE REMAINING OPERATIONS IN QUEUE FOR OLD RUNWAY CONFIGURATION MUST PROCEED TO THE NEW RUNWAY CONFIGURATION	
DEPARTURE TAXI TIME TO NEW RUNWAY	8 MINUTES
ARRIVAL FLYING TIME TO NEW RUNWAY	8 MINUTES
WIND CONDITIONS ARE SUCH THAT THE REMAINING OPERATIONS IN QUEUE FOR OLD RUNWAY CONFIGURATION CAN CONTINUE TO USE THAT CONFIGURATION <u>BUT</u> LACK OF LOW ALTITUDE WIND INFORMATION STILL RESULTS IN TWO LOST ARRIVAL AND TWO LOST DEPARTURE RUNWAY SLOTS	
TIME ASSOCIATED WITH LOST DEPARTURE SLOTS	4 MINUTES
TIME ASSOCIATED WITH LOST ARRIVAL SLOTS	3 MINUTES
TYPICAL COST PER AIRCRAFT DELAY MINUTE	
THE FOLLOWING DELAY COSTS ARE A SIMPLE EXTRAPOLATION OF THE 1976 TO 1980 AVERAGE DELAY COSTS CALCULATED OVER THE FLEET MIX THAT ARE PRESENTED IN REFERENCE 4-1	
DEPARTURE DELAY COST (1984 DOLLARS)	$30 PER MINUTE
ARRIVAL DELAY COST (1984 DOLLARS)	$50 PER MINUTE

TABLE 4.4: COMPONENT VALUES USED IN THE PER INCIDENT COST SAVINGS ESTIMATES (TABLE 4-3)

CURRENT PROBLEM	POTENTIAL SAVINGS PER RUNWAY SHIFT	ESTIMATED ANNUAL NUMBER OF AFFECTED RUNWAY SHIFTS	POTENTIAL SAVINGS PER YEAR
CORRECT RUNWAY SHIFT BUT TIMING COULD BE IMPROVED	\$7.2K \$3.0K	[.33] of (95 SHIFTS) [.67] of (95 SHIFTS)	\$225K \$190K
EXTRA RUNWAY SHIFT (1ST SHIFT NOT ALIGNED WITH WIND- 2ND SHIFT NECESSARY)	\$7.2K ① \$3.0K ①	[.33] of (60 SHIFTS) [.67] of (60 SHIFTS)	\$145K \$120K
EXTRA RUNWAY SHIFT (RUNWAY SHIFT MADE THAT PROVED TO BE UNNECESSARY WHEN THE WINDS BECAME KNOWN)	\$7.2K ① \$3.0K ①	[.33] of (45 SHIFTS) [.67] of (45 SHIFTS)	\$105K \$90K

TOTAL POTENTIAL SAVINGS PER YEAR IS \$875K

NOTE: ① COST SAVINGS DUE TO THE ELIMINATION OF AN UNNECESSARY RUNWAY SHIFT ASSUMED EQUAL TO THE SAVINGS DUE TO THE ELIMINATION OF THE TIMING PROBLEM

TABLE 4-5: ESTIMATED POTENTIAL ANNUAL COST SAVINGS FOR A DOPPLER RADAR BASED RUNWAY MANAGEMENT PRODUCT AT STAPLETON

2) The resulting exploratory discussions with three of these watch supervisors identified at least some of the runway management situations where the current lack of low-altitude wind information results in lost runway utilization and traffic delay. Also, an attempt was made in these discussions to quantify the potential annual benefit of the Gust Front Advisory in terms of reduced traffic delay.

3) The resulting calculation of this benefit is meant to provide insight into a methodology that can be used to make this estimate and to provide a first-cut approximation of this benefit for one airport - Stapleton.

4) This calculation only pertains to the delay savings to the aviation community due to a Doppler based runway management product. It does not reflect the potential delay reduction benefits that other Doppler based products may have. One example is the potential improvement in the utilization of the arrival and departure gates leading into and out of terminal area air space when thunderstorms are present. (Reference 4-2 presents a qualitative discussion of that potential benefit.)

5. ADDITIONAL OPERATIONAL INSIGHTS

The Stapleton project provided an opportunity to study the operational effects of low-altitude wind shears on runway operations at a major airport for a six week period. It provided the opportunity to:

1) Document the operational impact of several microbursts

2) Explore the general operational impact of wind shift lines

3) Document an unexpected wind shear feature (the microburst line) as a significant aviation hazard

4) Document examples of the complexity of the low-altitude wind shear environment faced by Stapleton pilots and controllers during the thunderstorm season.

Items (1) and (2) were discussed in the previous two sections and Items (3) and (4) are presented in this section.

5.1 THE MIRCOBURST LINE - DOCUMENTATION OF A SIGNIFICANT AVIATION HAZARD

In Doppler weather radar based studies over the last several years, NCAR personnel have observed multiple microbursts forming into a line structure on a number of occasions. The result is an elongated outflow feature that can have a lifespan far in excess of the 5 to 15 minutes associated with individual microbursts. Case studies describing the meteorology of this feature have started to appear in the scientific literature (Reference 5-1). CLAWS provided the first opportunity to observe and document the operational impact of this feature on an airport's runway operation.

Due to the appearance of these outflows on Doppler radar, NCAR has named these features "divergent lines". In an attempt to devise a name that would have some operational associations for the aviation community, these features are informally called "microburst lines" in this study.

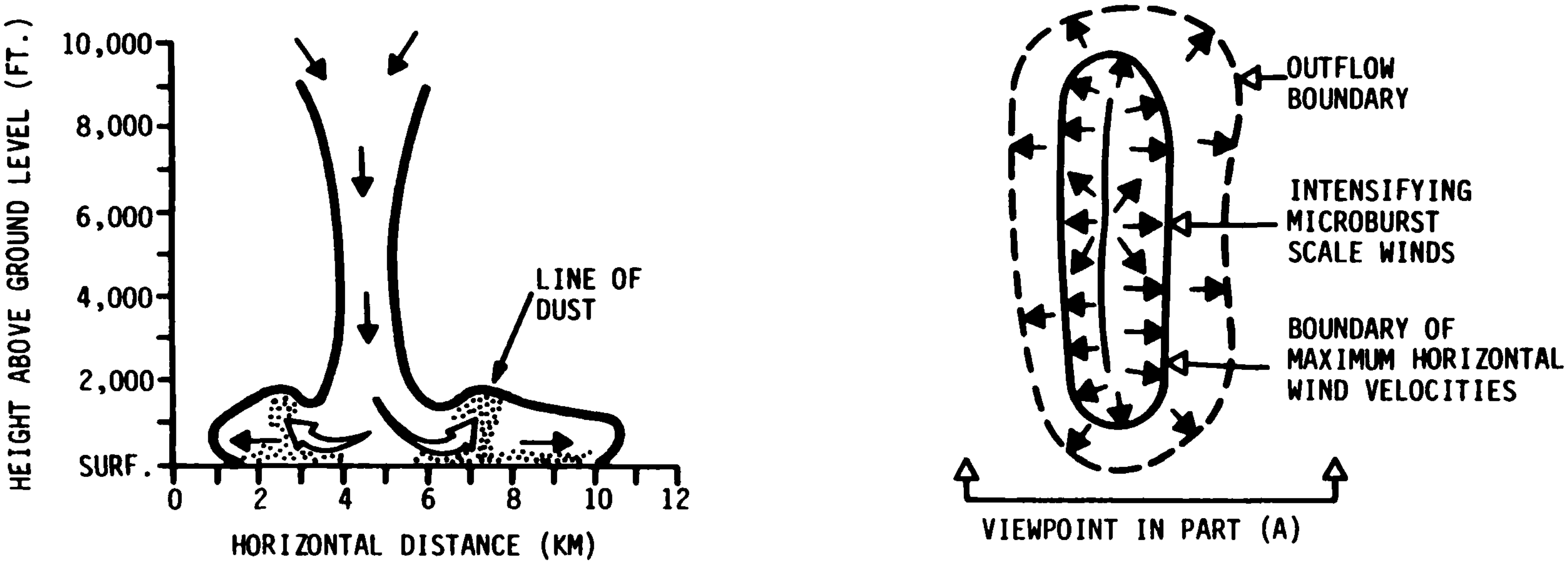
Based on discussions with NCAR personnel, the following profile of the microburst line is presented. The description should be considered preliminary in that the meteorological investigation of this feature is in its early stages. Figure 5-1 shows the basic wind flow structure of the microburst line. The dimensions of the outflow seem to typically be from 8 to 10 km wide and 20 to 25 km long. The distance between the peak to peak horizontal wind speeds across the outflow remain microburst-like at 4 to 6 km. Outflow wind speeds along the line can vary, with individual microbursts in the line being either significantly stronger or weaker than the line as a whole. At other times, the wind speeds along the outflow can be uniform.

During the six week operating period, five microburst lines were observed within five nautical miles of Stapleton center field. For the two lines that had the most operational impact, a time sequence of outflow position and extent relative to Stapleton's runways was obtained by reviewing the NCAR Doppler weather radar return tapes.

The first of these two cases, occurred on July 19, 1984. The documented line was the second, and the most disruptive, of two microburst lines that passed over Stapleton that afternoon. Figure 5-2 presents the position and extent of the line's outflow shown relative to Stapleton's runways at approximately half hour intervals. The microburst line is modelled on the outflow format introduced in Figure 5-1: (a) the central line represents the split in the outflow's wind direction, (b) the inner, heavy contour represents the location of the maximum horizontal wind speeds in the outflow and (c) the outer, dashed contour represents the extent of the outflow's lesser winds.

Figure 5-2 shows that the microburst line was located about nine nautical miles to the northwest of Stapleton center field at 5:17 pm. The line had come into existence before that time. At 5:36 pm, the NCAR meteorologists at the ATCT noted the microburst line as a line of dust about five nautical miles to the northwest of Stapleton. By 5:44 pm, the most intense winds of the line were about to pass over the airport and there was a microburst in the outflow portion of the line near center field. By 6:19 pm, the outflow had cleared Stapleton's runways, was weakening and continuing to move to the southeast. The main points of this example are that:

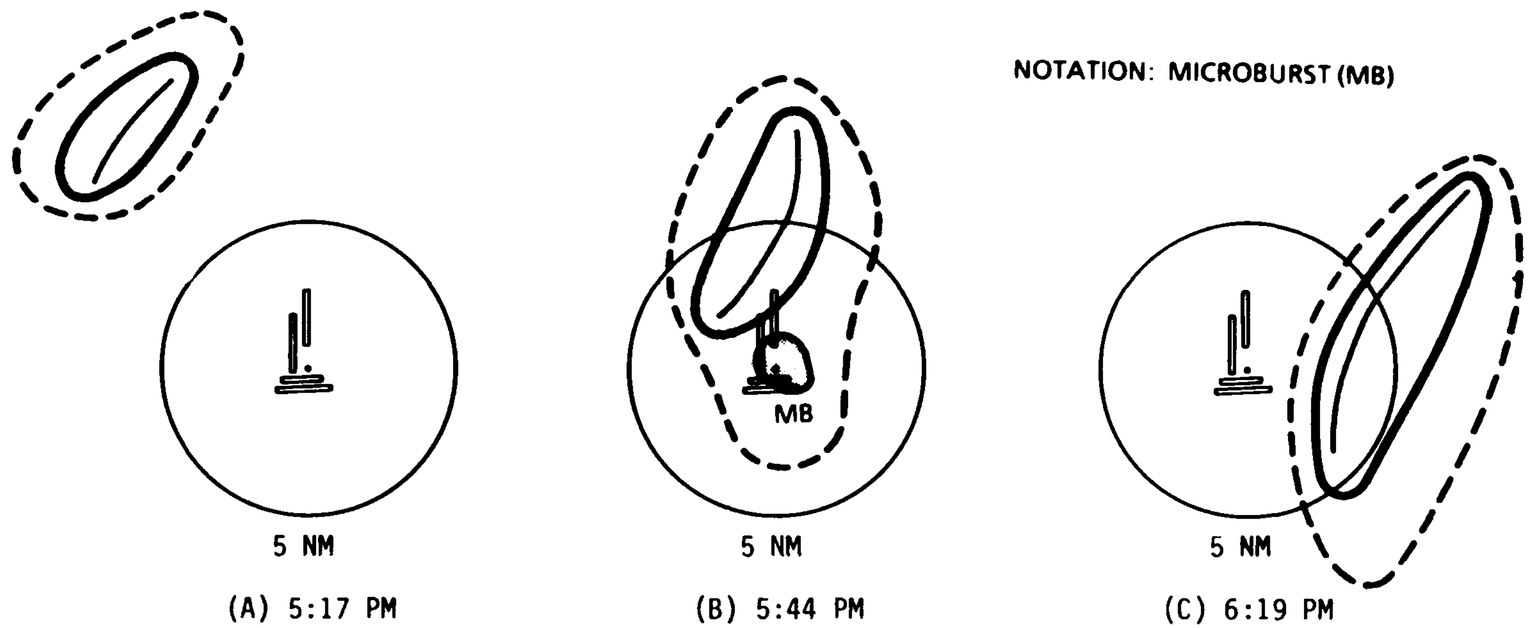
1) Microburst lines can be long-lived features - i.e., the observed portion of the lifespan was 62 minutes.



(A) VERTICAL STRUCTURE AS VIEWED FROM END OF LINE

(B) HORIZONTAL STRUCTURE OF OUTFLOW

FIGURE 5-1: BASIC MICROBURST LINE STRUCTURE (PRELIMINARY)



<u>**OPERATIONAL IMPACT OVER A 32 MINUTE PERIOD**</u>

(1) 12 MISSED APPROACHES

(2) STOPPED ARRIVAL OPERATIONS FOR 14 MINUTES

(3) STOPPED DEPARTURE OPERATIONS FOR 16 MINUTES

FIGURE 5-2: OPERATIONAL IMPACT OF THE SECOND JULY 19, 1984 MICROBURST LINE AT STAPLETON

2) Microburst lines can exhibit very high wind differentials across their outflows - i.e., a number of airport windows were blown out and the LLWAS registered 55 kt wind gusts on one side of the outflow over an eight minute period.

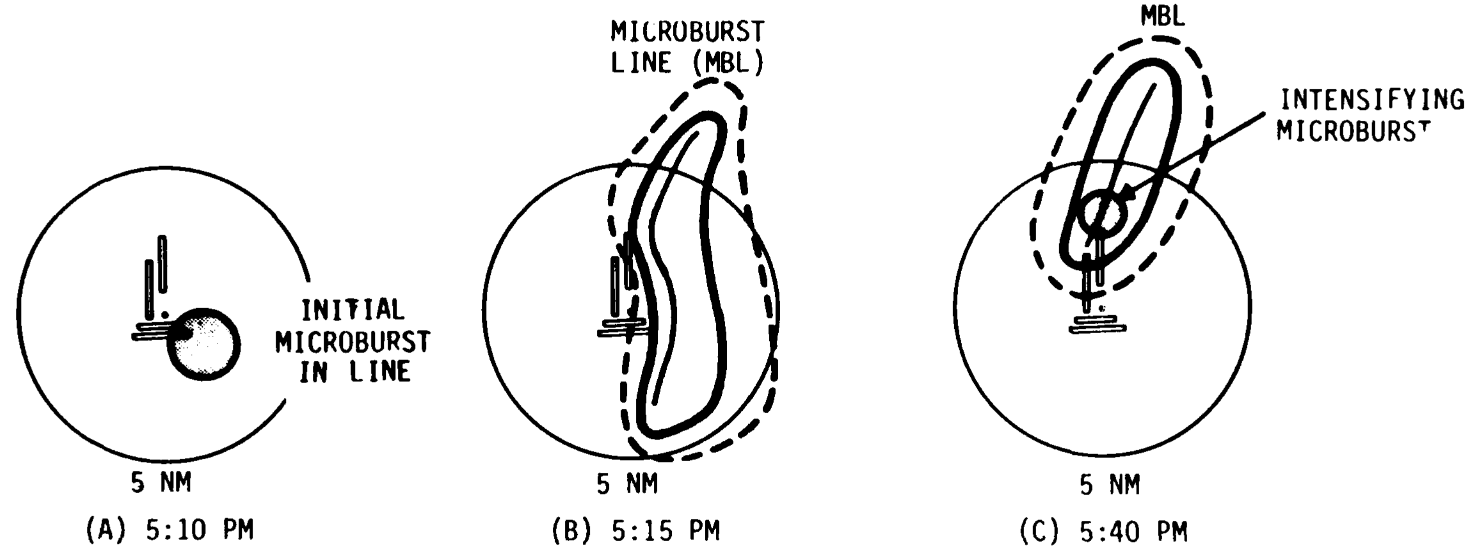
3) In contrast to individual microbursts, discussed in Section 3, a microburst line can cause extensive disruption of runway operations - i.e., over a 32 minute period, this line caused 12 missed approaches followed by a cessation of all attempted landings for 14 minutes and a cessation of takeoffs for 16 minutes.

4) This case study may represent a worst case microburst line example at Stapleton - i.e., at the end of this episode, the FAA watch supervisor in the ATCT commented "Worst wind shifts I have ever seen on duty in nine years" and one of the local controllers commented that "I have seen a couple nearly that bad."

5) The microburst line is quite different in character from a set of unorganized microbursts - e.g., the overall nature of this feature can be so different from the concept of individual microbursts that, in this episode, the NCAR team did not issue any microburst advisories.

As a result of this experience, NCAR decided that some sort of microburst line advisory should be provided for the remainder of the project. However, designing, introducing, and supporting a new product on short notice was not feasible. NCAR devised a procedure to adapt their microburst advisory to provide microburst line coverage. NCAR would issue a separate microburst advisory for each location that a microburst line intersected the runway operation. For example, if a microburst line overlaid the entire runway operation, NCAR would issue a microburst advisory for the approach end of the arrival runways, the departure end of the departure runways, and perhaps for the runways themselves.

Figure 5-3 presents a profile of the fifth and last microburst line to occur at Stapleton during the project. The line started out as a single microburst which rapidly formed into a line structure just to the east of the runways. The line slowly drifted towards the runways. By 5:40 pm, the older, southern portion of the line had dissipated. However, the microburst line remained intact and vigorous just to the north of the



MICROBURST LINE LIFETIME - APPROXIMATELY 50 MINUTES (5;10 P.M. TO 6:00 P.M. WHEN IT WAS DISSIPATING RAPIDLY)

OPERATIONAL IMPACT - STOPPED DEPARTURE OPERATIONS FOR 28 MINUTES

FIGURE 5-3: OPERATIONAL IMPACT OF THE JULY 30, 1984 MICROBURST LINE AT STAPLETON

airport. The line had totally dissipated shortly after 6 pm. The main points of this example are that:

1) The actual lifetime of this line was approximately 50 minutes,

2) The microburst line generated surface wind gusts of 38 kts on at least one side of the outflow (i.e., as measured by the LLWAS),

3) Arrival operations, which were landing from the west onto Runways 8L and 8R, were unaffected by the line even though the line was present on the arrival runways for part of the time (This is in agreement with the findings presented in Section 3 concerning the operational impact of microbursts.),

4) Conditions were such that departing pilots chose to delay their takeoffs over a 28 minute period. For the first 14 minutes, the pilots stayed on the ground due to cross winds in excess of 20 kts. on the departure runways, Runways 35L and 35R. The final 14 minutes, the pilots continued to stay on the ground due to an NCAR microburst advisory indicating the presence of the line just to the north of the departure runways and an NCAR "probable" hail advisory for that same area,

5) With one exception, the adapted microburst advisory service worked well in this case. When the initial, single microburst first developed into a line structure, the NCAR team issued an advisory for a "divergent line", instead of two or three microburst advisories that spanned the line. The divergent line advisory was probably not understood and was not passed on by the two local controllers. All other advisories were promptly passed on by the controllers.

Table 5-1 presents summary information for all five microburst lines. Microburst Lines 2 and 5 have been discussed in some detail. Microburst Line 1 caused four pilots to execute missed approaches and the FAA to shift arrival runways.

Microburst Line 3 was a line that existed a couple of miles to the west of the runways, dissipated and then reappeared over Stapleton's runways. While the line was

MBL No[1]	DATE (LOCAL TIME)	MAX. LLWAS WINDS	OPERATIONAL IMPACT	NUMBER OF NCAR ADVISORIES	COMMENTS
1	7-19-84 (4:30 PM)	36 KT GUSTS	(A) 4 MISSED APPROACHES (B) RUNWAY SHIFT	NONE - NCAR UNCERTAIN AS TO HOW TO CHAR THE EVENT IN THEIR MICROBURST ADVISORY FORMAT FOR BOTH MBL 1 AND MBL 2	
2	7-19-84 (5:45 PM)	55 KT GUSTS	(A) 12 MISSED APPROACHES (B) STOPPED ARRIVAL OP FOR 14 MINUTES (C) STOPPED DEPARTURE OP FOR 16 MINUTES (D) MULTIPLE RUNWAY SHIFTS		WATCH SUPERVISOR - "WORST WIND SHIFTS EVER SEEN ON DUTY IN NINE YEARS" LOCAL CONTROLLER - "HAVE SEEN A COUPLE NEARLY AS BAD"
3	7-27-84 (6:45PM)	LLWAS OUT OF SERVICE	(A) 1 MISSED APPROACH	4 MB ADVISORIES[2]	AIRCRAFT FLEW THROUGH THE MBL AT THE ADVISORY LOCATIONS BUT ONLY 1 OF THE 4 ADVISORIES VERIFIED
4	7-28-84 (5:30 PM)	16 KTS NO GUSTS	NONE	2 MB ADVISORIES[2]	AIRCRAFT FLEW THROUGH THE MBL AT THE ADVISORY LOCATIONS BUT WIND SHEARS NOT VERIFIED
5	7-30-84 (5:15 PM)	38 KT GUSTS	(A) STOPPED DEPARTURE OP FOR 28 MINUTES	3 MB ADVISORIES[2] 1 DIVERGENT LINE ADVISORY 1 HAIL ADVISORY	BASED ON ADVISORIES NO PILOT FLEW INTO THE MBL

NOTE [1] MBL = MICROBURST LINE
[2] MB = MICROBURST

TABLE 5-1: SUMMARY OF THE MICROBURST LINE CASES

to the west of Stapleton, NCAR issued one microburst advisory for the final approach paths to Runways 8L and 8R, which were being used for an occasional arrival. One pilot attempted to make an approach from the west and executed a missed approach without comment. When the line reappeared over both the arrival and departure runway operations, NCAR issued three advisories. Numerous arrival and departing pilots flew through the microburst line at the advisory locations but did not report any significant wind shears.

Microburst Line 4 was a similar situation. The line was over the airport runways and NCAR issued two microburst advisories - one for the arrival operation and one for the departure runways. Once again, numerous pilots flew through the microburst line at the advisory locations but did not report any significant wind shears.

These last two cases indicate that microburst lines can vary considerably in strength. Just as in the case of the microburst, an algorithm is needed that will identify when a microburst line is of operational significance. (See Section 3.1 for an example microburst algorithm.)

In summary, these five microburst line case studies:

1) Document that the microburst line can be a significant operational hazard to aviation.

2) Demonstrate that the microburst line can vary dramatically in strength and operational significance.

3) Indicate that operationally significant microburst lines may be a fairly common occurrence at Stapleton during the thunderstorm season.

5.2 THE STAPLETON LOW-ALTITUDE WIND SHEAR ENVIRONMENT

During the thunderstorm season, controllers and pilots at Stapleton are faced with a variety of low-altitude wind shear features on a routine basis. Up to this point in the report, the Stapleton wind shear environment has been described one feature and one episode at a time. This subsection characterizes this environment as a whole.

The six week project provided a sample of this environment over approximately half of the primary June through August thunderstorm season. Over that period, 68 individual, low-altitude, wind shear features were observed within five nautical miles of Stapleton center field:

1) Wind shift lines were the most numerous features - of the 32 lines observed, an estimated 25 caused a runway change.

2) Microbursts were almost as numerous at 30 - of which 13 were encountered by pilots, and 6 caused pilots either to execute missed approaches and/or to delay their takeoffs.

3) Microburst lines were far less numerous but not a rare feature - of the 5 lines observed, 3 had an operational impact, and 2 caused extensive disruption of runway operations lasting for about 30 minutes.

4) Tornadoes, within 5 nautical miles of Stapleton center field, are probably a rarity - the 1 observed tornado was of the type called a 'gustnado' (i.e., the smallest and least intense of the tornado classes) and caused 4 missed approaches and a runway shift.

Within five nautical miles of Stapleton center field, these wind shear features can either occur as relatively isolated features, in combinations, or in a succession with one feature rapidly following another. Of the 68 observed features, 31 appeared in isolation (i.e., 22 or 70 percent of the wind shift lines, 5 or less than 20 percent of the microbursts, and 4 or 80 percent of the microburst lines). Of the remainder, almost all involved a wind shift line in combination with one or more other wind shear features:

1) Wind shift line/one microburst (3 cases)

2) Wind shift line/two to four microbursts (5 cases)

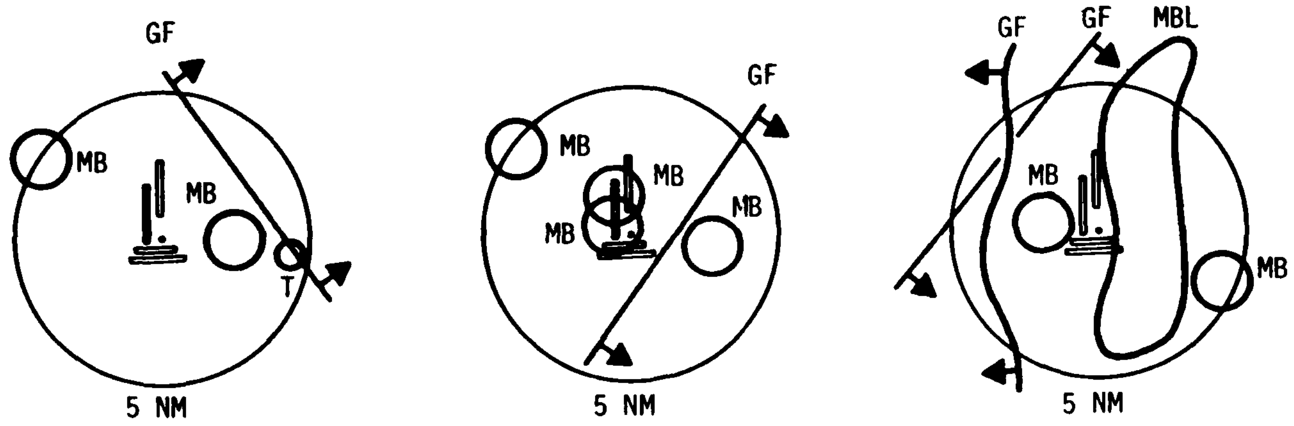
3) Wind shift line/two microbursts/tornado (1 case)

4) Two wind shift lines/two microbursts/one microburst line (1 case)

5) Two microbursts (2 cases).

Approximately 30 percent of the times that wind shear features were observed within the 5 nautical mile ring about Stapleton center field, multiple features were present. Of these 30 percent, Figure 5-4 presents three of the more complex wind shear situations faced by Stapleton controllers and pilots during the project.

The six week record of Stapleton's wind shear environment explains the interest of Stapleton's Air Traffic personnel in the operational uses of Doppler weather radar and their enthusiastic participation in this project. In addition, any future Doppler based product designed for ATCT use that is to provide full, low-altitude wind shear airport coverage should have the capacity to identify and characterize at least five separate wind shear features at one time.



(A) JULY 6, 1984
25 MIN. PERIOD

(1) GUST FRONT
(2) MICROBURSTS
(1) TORNADO

(B) JULY 7, 1984
30 MIN. PERIOD

(1) GUST FRONT
(4) MICROBURSTS

(C) JULY 30, 1984
65 MIN. PERIOD

(2) GUST FRONTS
(2) MICROBURSTS
(1) MICROBURST LINE

FIGURE 5-4: THREE EXAMPLES OF THE OBSERVED COMPLEXITY OF THE STAPLETON LOW ALTITUDE WIND SHEAR ENVIRONMENT

6. DISCUSSION OF RESULTS AND RECOMMENDATIONS

This section summarizes what has been learned from the CLAWS Project from an operational viewpoint and presents a list of recommendations.

6.1 THE MICROBURST ADVISORY SERVICE

Frequency of Occurrence of Microbursts Near Stapleton

The results confirm a 1982 NCAR finding that microbursts are a common feature in the Stapleton area during the thunderstorm season. Over the six week operating period, 30 microbursts were observed within five nautical miles of center field at Stapleton International Airport.

Frequency of Occurrence of Microbrust Encounters at Stapleton

The results establish that aircraft encounters with microbursts are not rare events at Stapleton. Over the six week period, arrivals encountered eleven microbursts along the last four miles of final approach and departures encountered four microbursts within three miles of takeoff roll initiation.

An Important Microburst Encounter Characteristic

The results support a 1982 NCAR finding that a microburst's outflow tends to build in strength over a several minute period. Operationally, this means that pilots and controllers should not take the first pilot report as indicative of the full strength potential of a microburst.

In CLAWS, it was found that the time between the first pilot report of a microburst encounter and the pilot reporting the outflow at maximum strength varied from 0 (i.e., the first report was for the maximum strength encounter) to 9 minutes and averaged about 3 minutes. Also, it was found that when missed approaches occurred due to a microburst, that it was the third and/or fourth pilots to encounter the microburst that broke off their approaches and, in one case, it was the eighth pilot.

Microburst Detection Rate with Doppler Radar Unit

The results support the view that a sophisticated, NEXRAD-like, Doppler weather radar can provide airport microburst coverage. Given the marginal siting of the NCAR radar relative to providing Stapleton coverage (see Section 2), the microburst detection rate with the radar was a surprisingly high 80 percent after a startup period. Overall, radar based advisories were issued for 20 of the 30 observed microbursts.

Microburst False Alarm Rate with Doppler Radar Unit

With one possible exception, there was a perfect correlation between the advisories issued for microbursts that hit on or near the landing/departing traffic pattern and the receipt of pilot reports of sighting or encountering a microburst. The worst case false alarm rate was 10 percent (i.e., at most, only one of the ten microburst advisories that should have been confirmed by corresponding pilot reports was not confirmed).

Timeliness of Radar-Based Microburst Advisories

The results demonstrate that radar-based microburst advisories can be timely. On average, each of these advisories was issued two minutes before the first pilot reported encountering the microburst and four minutes before the receipt of the pilot report of the encounter with the outflow at maximum strength.

Visual Sightings of Microbursts

The results suggest that a possible backup indicator of microbursts around an airport is the visual sighting of blowing dust in the microburst outflows as seen from the control tower cab windows. Of the ten microbursts missed by the Doppler radar at Stapleton, at least five were sighted from the tower cab by NCAR meteorologists.

During the project, several microburst advisories were issued by NCAR based solely on visual sightings. It was found that these advisories were too late with respect to warning the first pilot to encounter the microburst but that they tended to be timely relative to advising the pilot that would encounter the microburst outflow when it was at full strength.

Microburst Locations of Concern to Landing and Departing Pilots

The six week operating period provided a sample of pilot reports of microburst encounters and the associated missed approaches and delayed takeoffs that occurred.

The sample was large enough to permit one to start to define the area of microburst locations of concern to landing and departing pilots. The results of that effort are presented in Section 3 and discussed in Recommendation 2 at the end of this section.

Controller Reaction to the Microburst Advisory Service

In a post project debriefing, the concensus opinion of controllers was that the advisories increased operational safety and that the service was worthwhile.

6.2 AN INFORMAL GUST FRONT ADVISORY SERVICE

Partway through the project, NCAR initiated a simple, informal, Doppler radar based gust front (i.e., wind shift line) advisory service. NCAR would issue a verbal advisory to the control tower watch supervisor whenever a wind shift line was nearing Stapleton. The watch supervisor, who is responsible for planning and timing runway shifts, would be told the line's expected time of arrival at airport center field, its estimated maximum wind strength and its final wind direction. The service was informal in that the watch supervisors were free to use or ignore the advisories in planning and timing their wind-shift-induced runway changes.

Frequency of Occurrence of Wind Shift Lines Near Stapleton

As one would expect, the results show that wind shift lines are a common occurrence at Stapleton during the thunderstorm season. Over the six week operating period, 32 wind shift lines were observed nearing Stapleton.

Gust Front Advisory Performance

Results demonstrate that a very basic, Doppler radar based wind shift line advisory service can provide advisories with an average lead time of 17 minutes, an average error in predicted time of arrival of the line at airport center field of 4 minutes and an average error in predicted maximum wind strength of 7 knots.

Watch Supervisor Reaction to the Gust Front Advisory Service

This level of advisory performance was clearly acceptable to the Stapleton watch supervisors. In a post project debriefing, the concensus opinion of the watch supervisors was that these advisories made planning for runway changes due to wind shift lines much more efficient and that these advisories proved to be the greatest benefit of the program from an Air Traffic management standpoint.

Attempt to Quantify the Potential Advisory Benefit

In an attempt to quantify the potential benefit of this advisory, used for runway management purposes, follow-up discussions were conducted with three Stapleton watch supervisors. These discussions were brief and exploratory in nature and had as their goal:

1) The identification of the specific operational situations where this type of advisory could increase the efficiency of wind shift related runway changes (three situations were identified), and

2) For each of these situations, to attempt to quantify the improvement one could expect because of the advisory in the "typical" case and to quantify the number of times one could expect to encounter that situation during the course of a year at Stapleton.

The underlying result of these discussions was that wind-shift-related runway changes are frequent occcurrences, particularly during the thunderstorm season, and that these advisories could probably improve the planning and timing of the runway changes in just about every case.

Based on those discussions: (1) a methodology has been hypothesized for estimating the potential annual benefit at an airport for a runway management type Doppler product and (2) a first-cut estimate of the potential benefit has been calculated to be $875K per year (1984 dollars) for Stapleton.

6.3 THE MICROBURST LINE DOCUMENTED AS AN AVIATION HAZARD

During the course of the six week operation, NCAR observed several microburst lines in the vicinity of Stapleton. NCAR had observed these elongated outflows in earlier Doppler radar based studies but this was the first opportunity to document the impact of this feature on runway operations.

In response to their first microburst line experience at Stapleton, NCAR adapted its microburst advisory service to provide microburst line coverage. NCAR would issue a regular microburst advisory for each location that a microburst line intersected the landing and takeoff operations at Stapleton.

The Microburst Line - Its Potential Characterized

The results document that the microburst line can be a large, long-lived, low-altitude, wind shear feature with intense winds. During the six week operating period, the maximum observed outflow length was nearly 30 kilometers, lifetime was over one hour, and wind strength was an eight minute period of 55 knot gusts on one side of an outflow as measured by the Stapleton center field LLWAS sensor.

The Microburst Line - An Aviation Hazard

The results establish the microburst line as a significant hazard to runway operations during the thunderstorm season, at least at Stapleton. During the six week period, the maximum observed runway disruption, due to a microburst line, lasted for a 32 minute period. The disruption involved 12 missed approaches, stopped all arrival runway operations for 14 minutes, stopped all departure runway operations for 16 minutes and involved multiple runway changes. This was not a freak occurrence in that two other microburst lines also caused significant disruption to the runway operation during the operating period.

Usefulness of the Adapted Microburst Advisory Service to Cover Microburst Lines

Results show that these advisories were used to advantage operationally by pilots in at least one microburst line situation. Pilots awaiting clearance to start their takeoff roll, delayed their takeoffs for 14 minutes due to advisories for an intense microburst line off the end of the departure runway and just beyond the LLWAS sensors.

The Microburst Line can also be too Weak to be of Operational Significance

Results also show that some microburst lines can be too weak to be of operational significance. Microburst advisories were issued for two microburst lines that were so weak that landing and departing pilots flying through the outflows did not report any significant wind shears. This finding indicates that the initial radar-based algorithm for declaring when a microburst line is of sufficient strength to warrant an advisory, which was quickly devised by NCAR during CLAWS, needs to be refined.

6.4 RECOMMENDATIONS

CLAWS provided the FAA with the opportunity to gauge the operational usefulness of two very simple Doppler radar-based products for control tower use - the microburst and gust front advisories. The project demonstrated the usefulness of these two products at Stapleton - even in their present, primitive forms. It also provided a pool of operational experience in the use of these products. It is recommended that this pool of experience be used to start to define:

1) A Doppler radar-based pilot advisory product for universal local control use. With this product the controller, on a time permitting basis, would advise pilots on final approach and takeoff roll/initial climb of the type and strength of all operationally significant wind shears that the pilot should expect to encounter. This product should clearly identify all operationally significant microbursts, wind shift lines, and microburst lines in the vicinity of the runway operations, characterize their maximum wind shear potential, and map their locations and extent.

2) The advisory wording and procedures for each feature. Based on the CLAWS experience, perhaps a two level advisory should be considered for microbursts - a basic advisory and an extreme caution advisory. The extreme caution advisory would be for two situations: (A) for any microburst in those areas where landing and departing aircraft are near the ground and are particularly vulnerable to wind shear encounters (i.e., the last mile of final approach and the runway area where liftoff normally occurs) and (B) for those rare but intense microbursts, which can exhibit wind differentials approaching 100 kts across their outflows, when they are located in the areas where landing and departing aircraft are at altitudes below 1000 ft. above-ground-altitude (AGL). In all other situations where a microburst will be encountered by an aircraft below 1000 ft. AGL, a basic microburst advisory, like the one used in CLAWS, would be issued to pilots.

3) A Doppler-based runway management product for universal watch supervisor use in planning and timing runway shifts. It is envisioned that this product would be similar to the local control product in that it would show all

operationally significant low-altitude, wind shear features (e.g., wind shift lines, microburst lines, and microbursts) in the vicinity of the airport. The two main differences in the products would be that the watch supervisor's product would: (A) normally be set to a scale so the supervisor could monitor all line structures approaching the airport (e.g., within 10 nautical miles of the airport) and (B) have predictive capabilities that could perhaps be interrogated, such as the estimated time of arrival of a wind shift line at the airport and the probable duration of particular wind components in the line (e.g., winds over 20 kts at right angles to the departure runway).

Beyond the recommendation to tap the unique pool of operational experience at Stapleton in the use of Doppler-based products, three other recommendations are put forth:

4) Review the merits of the hypothesized methodology for estimating the potential annual savings for a Doppler radar-based runway management product. If the preliminary estimate of this savings calculated for Stapleton is realistic, the overall annual savings on a nation-wide scale should be substantial.

5) Explore the operational impact of low-altitude, wind shear features and the potential role of Doppler radar-based ATC products at other airports in addition to Stapleton. This activity is important for two reasons: (A) to determine if the Stapleton experience with these features is unique or is typical to a group of airports; (B) to understand in detail how these features impact operations at airports other than Stapleton and the specific role of Doppler-based products in reducing that impact.

6) Continue to take the opportunity to expand FAA sponsored, Doppler weather radar-based, field studies (e.g., like the 1982 JAWS Project) and operational projects (e.g., like the 1984 CLAWS Project) to define/refine a set of products for ATC and aviation community use. The CLAWS Project represents the start in defining two such products, tailored to operational needs: a low-altitude, wind shear, pilot advisory product and a runway management product.

GLOSSARY

AGL	-	Height Above Ground Level
ATC	-	Air Traffic Control
ATCT	-	Air Traffic Control Tower
CLAWS	-	Classify, Locate, and Avoid Wind Shear Project
CP-2	-	A Doppler Weather Radar Facility Maintained by NCAR
FAA	-	Federal Aviation Administration
JAWS	-	Joint Airport Weather Studies Project
LLWAS	-	Low Level Wind Shear Alert System
NCAR	-	National Center for Atmospheric Research
NEXRAD	-	Next Generation Weather Radar
PIREP	-	Pilot Report of Observed or Encountered Weather

REFERENCES

1-1 McCarthy, John, and Wilson, James, "The Classify, Locate, and Avoid Wind Shear (CLAWS) Project at Denver's Stapleton International Airport" (To be published).

1-2 McCarthy, John and Wilson, James, "The Classify, Locate, and Avoid Wind Shear (CLAWS) Project at Denver's Stapleton International Airport: Operational Testing of Terminal Weather Hazard Warnings With an Emphasis on Microburst Wind Shear," Preprints Second International Conference on the Aviation Weather System, American Meteorological Society, Boston, 1985.

3-1 Fujita, T.T., "Downbursts and Microbursts - An Aviation Hazard," Preprints 19th Conference on Radar Meteorology, American Meteorological Society, Boston, 1980.

3-2 Committee on Low-Altitude Wind Shear and its Hazard to Aviation, Low-Altitude Wind Shear and Its Hazard to Aviation, National Academy Press, Washington D.C., 1983.

3-3 Fujita, T.T., "Microburst Wind Shear At New Orleans International Airport, Kenner, Louisiana on July 9, 1982," Satellite and Mesometeorology Research Project Paper 199, University of Chicago, January 12, 1983.

3-4 Fujita and Caracena, "An Analysis of Three Weather-Related Aircraft Accidents," Bulletin of the American Meteorological Society, Vol. 58, No. 11, November 1977.

4-1 Federal Aviation Administration/Aviation Policy Office, "Airfield and Air Space Capacity and Delay Analysis," FAA-APO-81-4, December 1981.

4-2 Stevenson, L., "Thunderstorm Impact on Denver Air Traffic Control Operations and the Role of NEXRAD," U.S. Department of Transportation, Transportation Systems Center, DOT-TSC-RSPA-84-1, April 1984.

5-1 Kessinger, Hjelmfelt, Wilson, "Low-Level Microburst Wind Structure Using Doppler Radar and PAM Data," Preprints 21st Conference on Radar Meteorology, American Meteorological Society, Boston, 1983.

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